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Air Pollution Concentrations Associated with Stagnation and Restricted Visibility, Eastern North American, August 1976

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July 1980

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July 1980

AIR POLLUTION CONCENTRATIONS ASSOCIATED WITH STAGNATION AND RESTRICTED VISIBILITY Eastern North America, August 1976

by

Gerard A. DeMarrais
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16. ABSTRACT

August 16 to 22 was designated as a stagnation period for a large part of the eastern United States by the Korshover technique, and Lyons and his associates judged August 16 to 28 to be a stagnation period. The effect of the 13 days of stagnation on five pollutants (total suspended particulates, carbon monoxide, sulfur dioxide, ozone and sulfates) and the association of various pollutants with restricted visibility are discussed in detail. Because long-range transport contributes to high concentrations of pollutants, trajectory analyses are included to indicate the approximate source-receptor relationships.

17. KEY WORDS AND DOCUMENT ANALYSIS

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has associated sulfate concentrations as low as 10 μg/m³ with adverse health effects[10]. (Additional research into the health effects associated with high sulfate concentrations has been authorized by Congress[11].)

The methods used to measure total suspended particulates, sulfur dioxide, carbon monoxide, and ozone were the standard methods recommended by the U.S. Environmental Protection Agency (EPA) and are described in detail in a World Health Organization publication[12]. A description of the method by which sulfates were measured is found in an air pollution monitoring handbook[13].

The United States standards (levels which are not to be exceeded more than once a year) are as follows: (1) for total suspended particulates, a 24-hour average of 260 μg/m³; (2) for sulfur dioxide, a 24-hour average of 365 μg/m³ (0.14 ppm); (3) for carbon monoxide, a maximum one-hour average of 40 μg/m³ (35 ppm); and (4) for ozone, a maximum one-hour average of 235 μg/m³ (0.12 ppm) (the standard was 160 μg/m³ but on January 26, 1979 was revised to the current value). Because there is no United States standard for sulfates, the concentration of 10 μg/m³ mentioned above is used as a reference.

TRAJECTORY ANALYSES

Transport of pollutants by surface winds and winds aloft is evaluated by trajectory analyses. The trajectories were calculated by the Heffter-Taylor method[14] and the analyses are for the layer from the surface to 1000 meters above the surface. (It is assumed that the bulk of the pollutants are transported in this layer. Morning mixing heights over the area averaged less than 300 meters and afternoon mixing heights averaged 1500 meters during August 16-28, 1976.) These trajectories were calculated from rawinsonde observations at 7 a.m. and 7 p.m. and from winds aloft observations made at 1 a.m. and 1 p.m. each day. For all the calculations, data were gathered within a radius of 300 nautical miles (556 km) of the observation station; a point was determined along the trajectory every 3 hours.

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AFFILIATION

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ABSTRACT

August 16 to 22 was designated as a stagnation period for a large part of the eastern United States by the Korshover technique and Lyons and his associates judged August 16 to 28 to be a stagnation period. The effect of the 13 days of stagnation on five pollutants (total suspended particulates, carbon monoxide, sulfur dioxide, ozone and sulfates) and the association of various pollutants with restricted visibility are discussed in detail. Because long-range transport contributes to high concentrations of pollutants, trajectory analyses are included to indicate the approximate source-receptor relationships.

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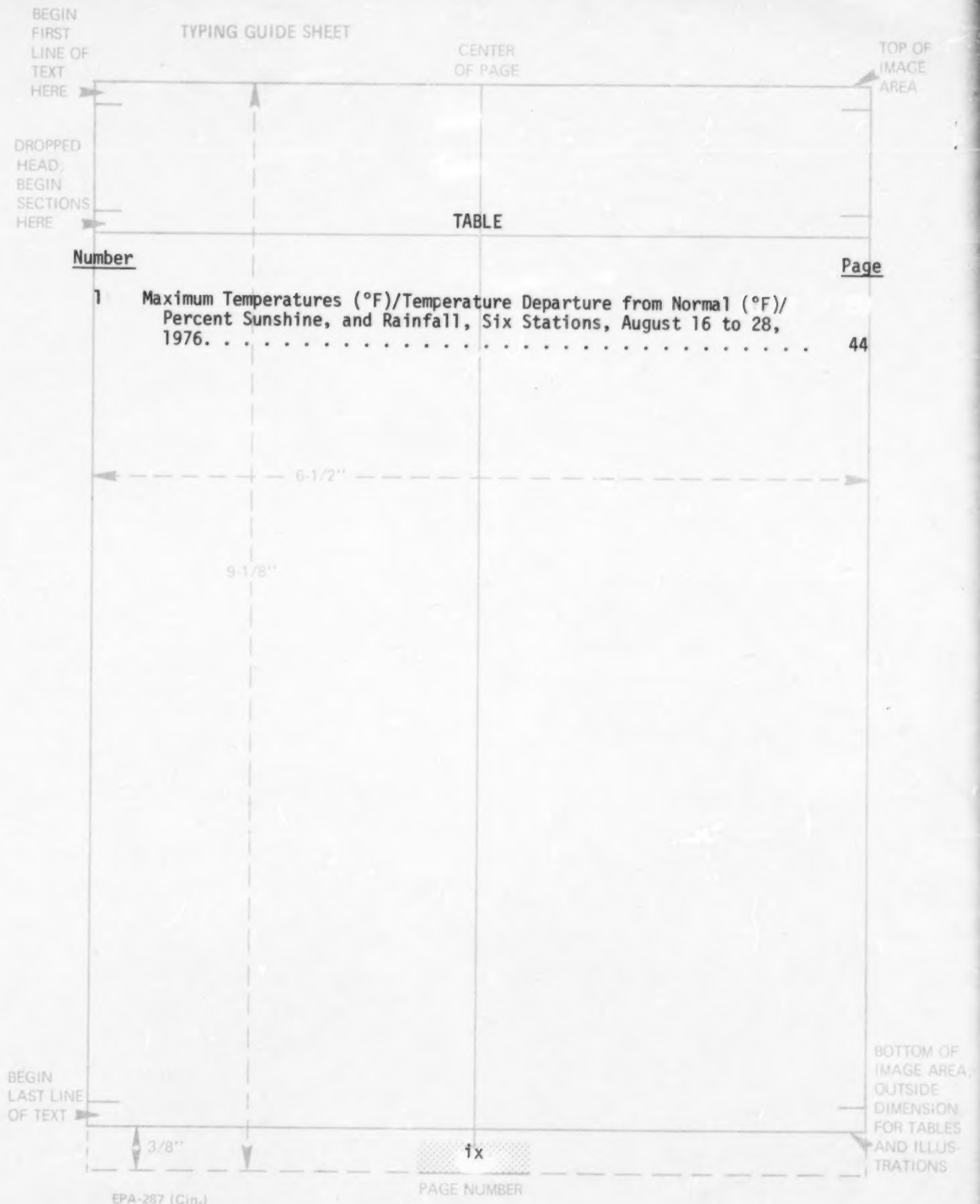
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SECTION 1

INTRODUCTION

A major contributing factor to the air pollution disaster which occurred in Donora, Pennsylvania in 1948 was a warm high pressure area which slowly moved over the area[1]. The slow movement and stable structure of the anticyclone allowed pollutants to accumulate to harmful levels. This phenomenon was called a stagnating high pressure area. In 1956 Korshover devised a semi-objective technique for determining when stagnating high pressure systems persisted over an area, and he prepared a climatology on the frequency of these systems[2]. In 1975 Korshover updated his summary[3]. Using ozone concentrations from four cities and the Korshover method of designating stagnation, Altshuller[4] concluded that only a small percentage of site-days with concentrations exceeding 8 pphm occurred in stagnation areas.

In this investigation a stagnation period is selected and the temporal and spatial variations in concentrations of five pollutants over the large area of stagnation are examined. According to Korshover, one of the most long lasting and widespread episodes of stagnation occurred over the eastern United States from August 16 to 22, 1976. He considered the episode to end on August 22 because a very weak front moved across the stagnation area on August 23, 1976. Lyons et al.[5] designated thirteen days from August 16 to 28, 1976 as the period for this episode because they did not feel the front ended the stagnation conditions. Since Altshuller acknowledged that the Korshover criteria could be too rigorous, it was decided to evaluate the entire period designated by Lyons et al. August 16 to 28. The pollutant concentrations analyzed are those for total suspended particulate, sulfur dioxide, carbon monoxide, ozone and sulfate. Included in the analyses are daily visibility summaries which Lyons et al. compiled, and sulfate data compiled

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by Whelpdale[6] in a special study over southeastern Canada. Finally, the long-range transport which likely occurred during the episode is shown by trajectory analyses for the surface-to-1000-m layer.

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SECTION 2

CONCLUSIONS

The analyses of air quality data and meteorological data for the eastern United States and southeastern Canada for August 16 to 28, 1976 demonstrated the following:

During the thirteen-day stagnation period, total suspended particulate, (TSP), sulfur dioxide, and carbon monoxide did not increase nor were high concentrations of any of these pollutants found. This result may have been due to the fact that this episode occurred in the middle of the summer, the period when concentrations of these pollutants are usually low. None of these pollutants appeared to contribute to the restricted visibility observed over southeastern Canada and northeastern United States from August 21 to 28.

Ozone concentrations increased during the initial days of stagnation; remained moderate (8 pphm to 12 pphm) for several days; were temporarily reduced on August 23 as a cold front moved through the area; were uniformily moderate or high (>12 pphm) on August 24 and 25; and decreased again as rain became more widespread from August 26 to 28. Anticyclonic flow predominated during the 13 days according to the trajectory analyses. The ever-shifting center of this flow constantly changed source-receptor relationships. In spite of the changing source-receptor relationships, the same three north-south elongated areas of high ozone concentrations reappeared on 5 days, suggesting that either numerous diverse sources or nearby large area sources, which were little affected by directional shifts, caused the high concentrations. The ozone concentrations were moderate and high before the visibility became restricted, and at most locations were low during the last 3 days with restricted visibility. The spatial correlation between areas of restricted visibility and areas

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of moderate and high ozone concentrations was poor.

Sulfate concentrations were high (>10 μg/m³) on the first day of stagnation and even higher on August 22 and 28 (the 3 days for which data are available) over the eastern United States. Over Canada, the sulfate concentrations were low initially; became high on the third day in response to a flow from the west; were temporarily lowered with the frontal passage of August 23; and thereafter were high until August 28. After the initial days of high concentrations the flow was from the southwest. While there were some high sulfate concentrations before the visibility was restricted, there did appear to be spatial agreement between the areas of restricted visibility and the areas of high sulfate concentrations.

This thirteen-day stagnation period was one in which both the ozone and sulfate concentrations increased and were at high levels over large areas much of the time. The episode of high concentrations began in the period designated as stagnant by the Korshover technique. That this semi-objective technique indicated that the stagnation ended with the passage of the front through the area on August 23, was a shortcoming; the front was so weak that it had little effect on the pollution concentrations.

The restricted visibility during the stagnation was associated more strongly with high sulfate concentrations than with high or moderate ozone concentrations.

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SECTION 3

BACKGROUND AND METHODS

DESIGNATING STAGNATION, HIGH CONCENTRATIONS DURING STAGNATION AND THE AUGUST 16-22, 1976 EPISODE

The team of meteorologists investigating the air pollution disaster in Donora, Pennsylvania in 1948[1] formulated a prediction model by which the stagnating high pressure systems associated with air pollution could be anticipated. Korshover improved the model and developed a semi-objective technique[2] (not a forecast) for designating when stagnation conducive to poor air quality persisted for 4 or more days over large areas of the eastern United States. In 1956 Korshover presented a twenty-year climatological summary of the occurrences of prolonged stagnating conditions[2] and in 1975 he updated the summary[3]. Korshover's criteria for stagnation are the following: (1) the area involved was 4 degrees (4° latitude by 4° longitude) square or larger; (2) the anticyclone had a warm core (warm anticyclones are typically slow moving while cold-core anticyclones generally move rapidly); (3) the geostrophic wind each day was 15 knots or less (this would generally mean a maximum hourly surface wind speed of 8 mph or less and no winds greater than 25 knots at any level below 500 mb [approximately 18,000 feet above mean sea level]); (4) no precipitation occurred on the affected area; and (5) no frontal areas overlapped the area. While these criteria are very restrictive, there were 290 episodes over the eastern United States between 1936 and 1975[3], that is more than seven stagnation episodes of 4 days or more each year, on the average.

In the 1960's, two reports[7,8] showed that high concentrations of some air pollutants occurred with slow-moving high pressure areas in late November 1962 and 1966; temporal and spatial variations of pollutants were also reported. These reports did not discuss marked inconsistencies

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in the results, namely, that adjacent stations reported widely different concentrations and that peak concentrations of individual pollutants occurred in a random pattern.

The area over which stagnation, as defined by Korshover, occurred during August 16 to 22, 1976 extends in a northeast-southwest direction and is depicted in Figure 1. The latitude-longitude grid points showing 6 and 7 days of stagnation show that the center of the area of stagnation remained fairly constant throughout the period. The area to the southwest had 4 days of stagnation early in the seven-day period while the areas in the north and east had 4 and 5 days of stagnation late in the period.

INVESTIGATION OF LYONS, ET AL.

A group of meteorologists using earth satellites to detect air pollution episodes selected August 16 to 28, 1976, as a stagnation period in which an episode occurred[5]. Their documentation included: (1) mid-day visibility charts based on observations from 300 airport sites, and (2) confirming analyses of the continuous movement of visibile "smog blobs" employing the Manual Computer Interactive Data Acquisition System (MCIDAS) technique (using digital densitometric analyses) and data from the GOES-East meteorological satellite. Sulfate data for the eastern United States were not available by the end of 1978 when the group published their results.

Their pictorial summary of the development and movement of the smog blob for August 17 to 28, 1976, is shown in Figure 2. In each of the twelve parts (each depicting the mid-day conditions) of Figure 2 the following are shown; (1) the locations of fronts and centers of high and low pressure; (2) the pressure pattern (shown by the lines of equal pressure--isobars); and (3) areas of restricted visibility (the light stipple denotes areas of 5.5 to 9.2 km [about 4 to 6 miles] visibility and the darker stipple marks areas of less than 5.5 km visibility). All of the phenomena depicted on these charts are discussed in the analyses of air pollution concentrations which follow. However, these charts show two important features apart from pollutant concentration. First,

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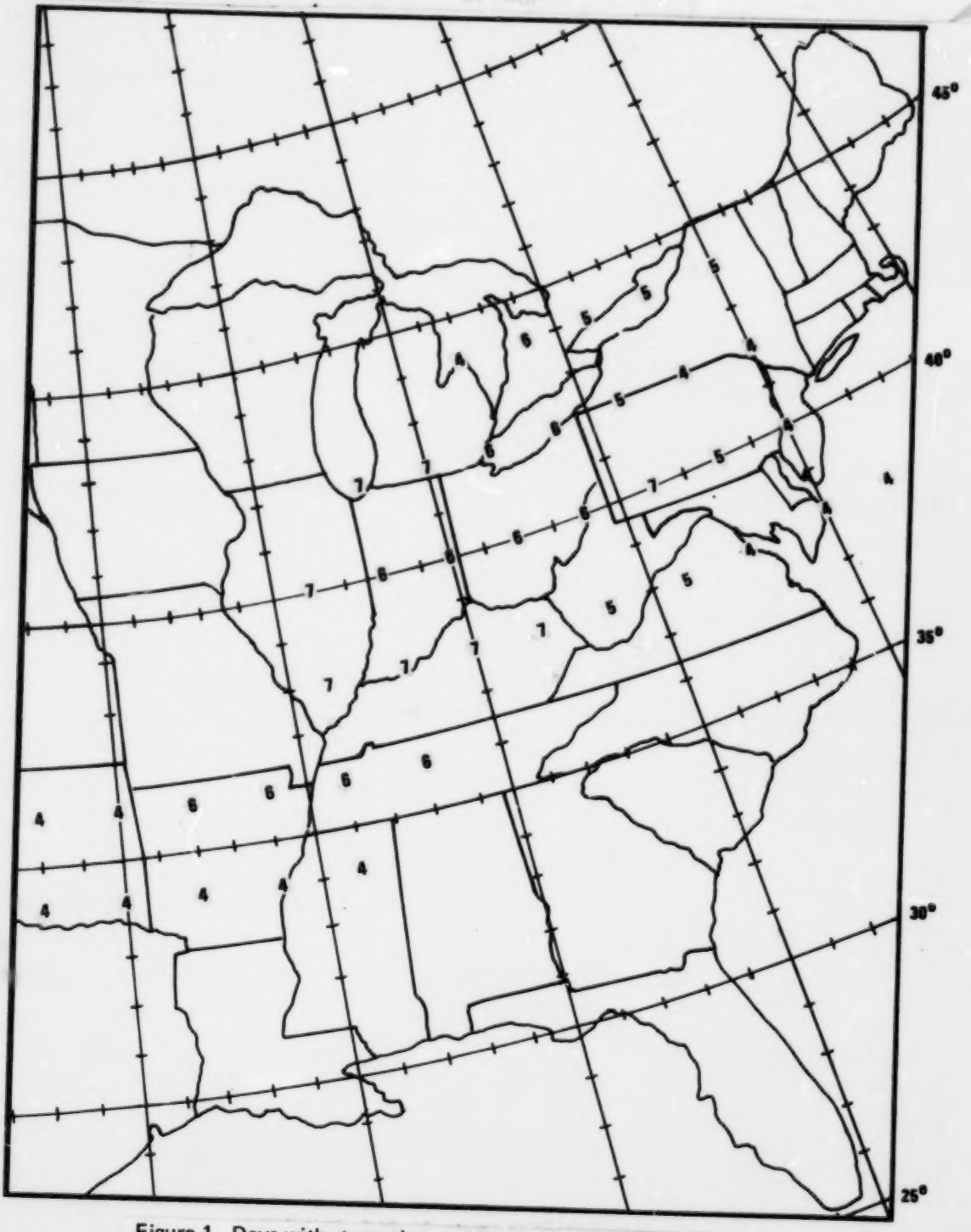

Figure 1. Days with stagnation conditions, August 16-22, 1976.

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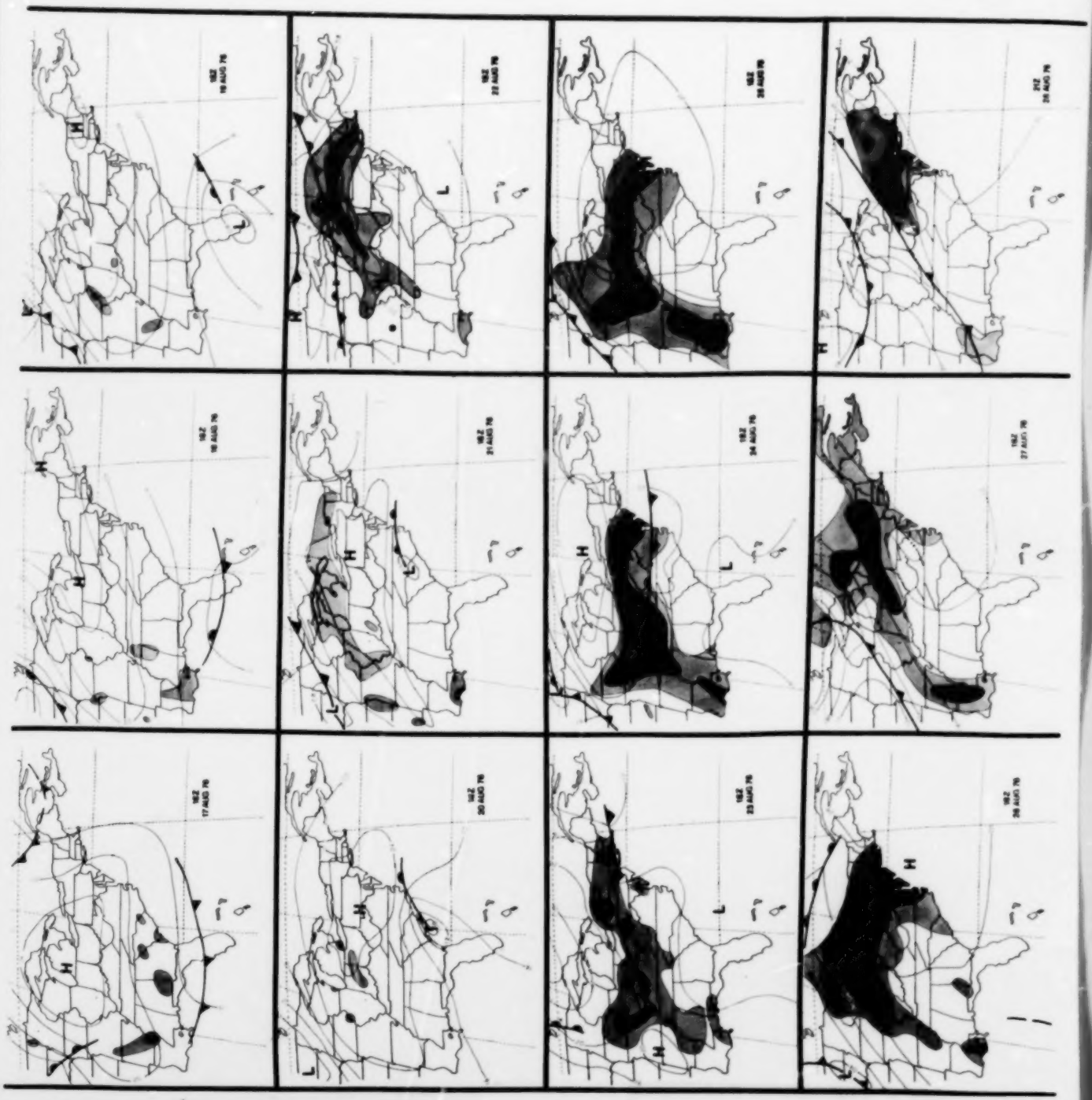

Figure 2. Surface synoptic maps, 1300 EST, August 17-28, 1976 with low visibility areas indicated. Isobars at mb intervals (Light stipple = 4 to 6 miles visibility; dark stipple = less than 4 miles visibility). (Courtesy of W. A. Lyons)

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there was no reduction of visibility over a statewide or greater area before the next-to-last day (August 21) of the Korshover stagnation period. And second, the passage of the front on August 23 (see appropriate part of Figure 2), which Korshover considered the end of the stagnation period, only temporarily reduced the visible pollution episode.

CANADIAN INVESTIGATION

The Department of Fisheries and Environment of Canada has undertaken a comprehensive program to investigate the long-range transport of air pollutants in eastern Canada. In August 1976, as part of this program, they conducted an intense sampling program[6]. The names and locations of the Canadian sulfate sampling sites are shown in Figure 3. Because the data provided in this Canadian investigation contain daily sulfate concentrations for a large network of stations on the northern boundary of the stagnation area and restricted visibility area, they are included in this report. On a majority of days these sulfate data are the only data available, Thus, these Canadian data supplement the data that were collected by stations in the United States on August 16, 22, and 28. In the sulfate discussion which follows, there are two five-part figures, comparable to Figure 2, showing the twenty-four-hour concentrations for August 17 to 21 and August 23 to 27.

AIR POLLUTANTS - TOTAL SUSPENDED PARTICULATES, SULFUR DIOXIDE, CARBON MONOXIDE, OZONE, AND SULFATES

In order to determine the effects of prolonged meteorological stagnation on air quality, the day-to-day variations of three primary pollutants, total suspended particulates, sulfur dioxide, and carbon monoxide, and two secondary pollutants, ozone and sulfates, were analyzed. Secondary pollutants are not emitted in the form in which they are measured but develop by reactions in the ambient air.

National ambient air quality standards (NAAQS) for total suspended particulates, sulfur dioxide, carbon monoxide, and ozone have been promulgated in the Federal Register (April 30, 1971)[9]. There is no standard for sulfates as yet in the United States; a preliminary report

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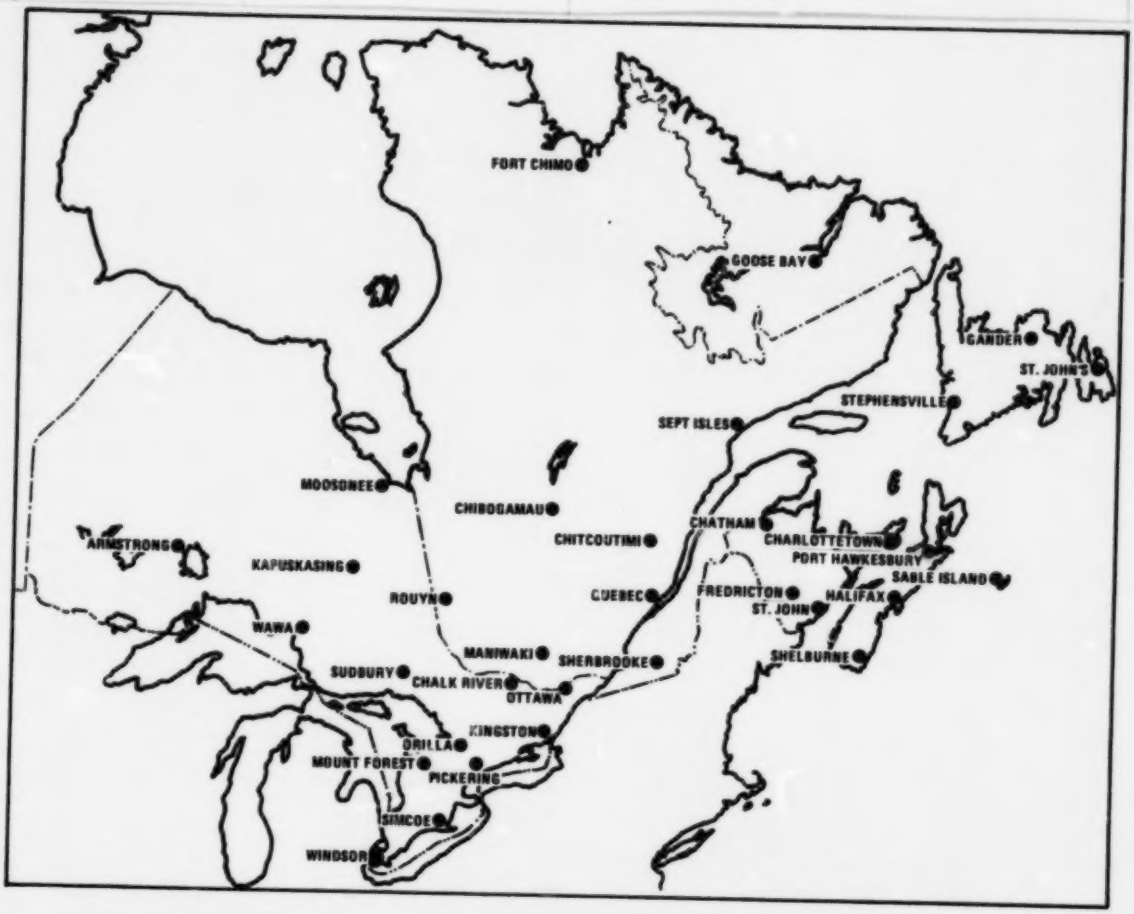

Figure 3. Names and locations of sulfate monitoring sites in southeastern Canada.

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has associated sulfate concentrations as low as 10 g/m with adverse health effects[10]. (Additional research into the health effects associated with high sulfate concentrations has been authorized by Congress[11].)

The methods used to measure total suspended particulates, sulfur dioxide, carbon monoxide, and ozone were the standard methods recommended by the U.S. Environmental Protection Agency (EPA) and are described in detail in a World Health Organization publication[12]. A description of the method by which sulfates were measured is found in an air pollution monitoring handbook[13].

The United States standards (levels which are not to be exceeded more than once a year) as folloare as follows: ws(1) for total suspended particulates, a 24-hour average of 260 $\mu g/m^3$; (2) for sulfur dioxide, a 24-hour average of 365 $\mu g/m^3$ (0.14 ppm); (3) for carbon monoxide, a maximum one-hour average of 40 $\mu g/m^3$ (35 ppm); and (4) for ozone, a maximum one-hour average of 235 $\mu g/m^3$ (0.12 ppm) (the standard was 160 $\mu g/m^3$ but on January 26, 1979 was revised to the current value). Because there is no United States standard for sulfates, the concentration of 10 $\mu g/m^3$ mentioned above is used as a reference.

TRAJECTORY ANALYSES

Transport nsport of pollutants by surface winds and winds aloft is evaluated by trajectory analyses. The trajectories were calculated by the Heffter-Taylor method[14] and the analyses are for the layer from the surface to 1000 meters above the surface. (It is assumed that the bulk of the pollutants are transported in this layer. Morning mixing heights over the area averaged less than 300 meters and afternoon mixing heights averaged 1500 meters during August 16-28, 1976.) These trajectories were calculated from rawinsonde observations at 7 a.m. and 7 p.m. and from winds aloft observations made at 1 a.m. and 1 p.m. each day. For all the calculations, data were gathered within a radius of 300 nautical miles (556 km) of the observation station; a point was determined along the grajectory every 3 hours.

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Trajectory segments were linked together to produce a complete trajectory ending at four times daily, 1 and 7 a.m. and 1 and 7 p.m. In this report, the trajectories for each receptor-city show the movements of the previous 48 hours in 12-hour segments for ending times of 7 a.m. and 7 p.m. These trajectories are, at best, approximations and become progressively less accurate with each added segment; a point on a trajectory indicates a general area and not a specific location where a parcel was located at an earlier time. Because the areas with stagnation (Figure 1) and restricted visibility (Figure 2) included locations on both sides of the United States Canadian border the following cities were used as receptors: Sudbury, Ontario; Ottawa, Ontario; Chicago, Illinois; Detroit, Michigan; Youngstown, Ohio; Albany, New York; Boston, Massachusetts; St. Louis, Missouri; Louisville, Kentucky; Washington, D.C.; Memphis, Tennessee; and Asheville, North Carolina. Because of the high pollutant concentrations observed in the Louisiana area, the transport into that area was also evaluated and the discussions concerning this area are based on trajectories for Baton Rouge. Trajectories for eight additional locations were calculated (and used in the evaluations of air movements), but because of space limitations, are not included in this presentation.

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SECTION 4

RESULTS

TOTAL SUSPENDED PARTICULATES

Although there are TSP data for more than 1500 stations in the eastern United States for August 1976, only seven stations had data for each day from August 16 to 28. Approximately 40 stations had data on TSP for 10 of the 13 days and about 25 percent of the stations monitored had data for 3 primary sampling days, August 16, 22 and 28. The data for twenty-four hour concentration of TSP from this aggregation of stations, supplemented by similar data from Canadian stations[6], were used to prepare maps showing the spatial distribution of concentrations on each day. The number of monitoring sites used in the analysis on the various days ranged from 24 to 170. Maps for the 3 days with the most abundant TSP data, August 16, 22 and 28, are shown in Figures 4, 5 and 6.

The TSP concentrations on the first day of the stagnation period, August 16, are shown in Figure 4. Although the range of values within the area was large, all concentrations were markedly less than the standard. The variation in values from station-to-station depicted in this figure were fairly consistent throughout the year. An examination of all the data for 1976 showed that stations with higher concentrations, like those in central Alabama, eastern Ohio, northern West Virginia, southeastern Michigan and southeastern Wisconsin, generally showed relatively high concentrations at all times. Similarly, the stations showing moderate and low values during the stagnation period did so fairly consistently throughout the year.

On August 17, TSP data from 45 stations indicated that concentrations were only slightly higher than they were on August 16. A striking exception occurred at a rural site in Jasper County, Indiana, called Asphaltum. There, the highest concentrations among all stations, for

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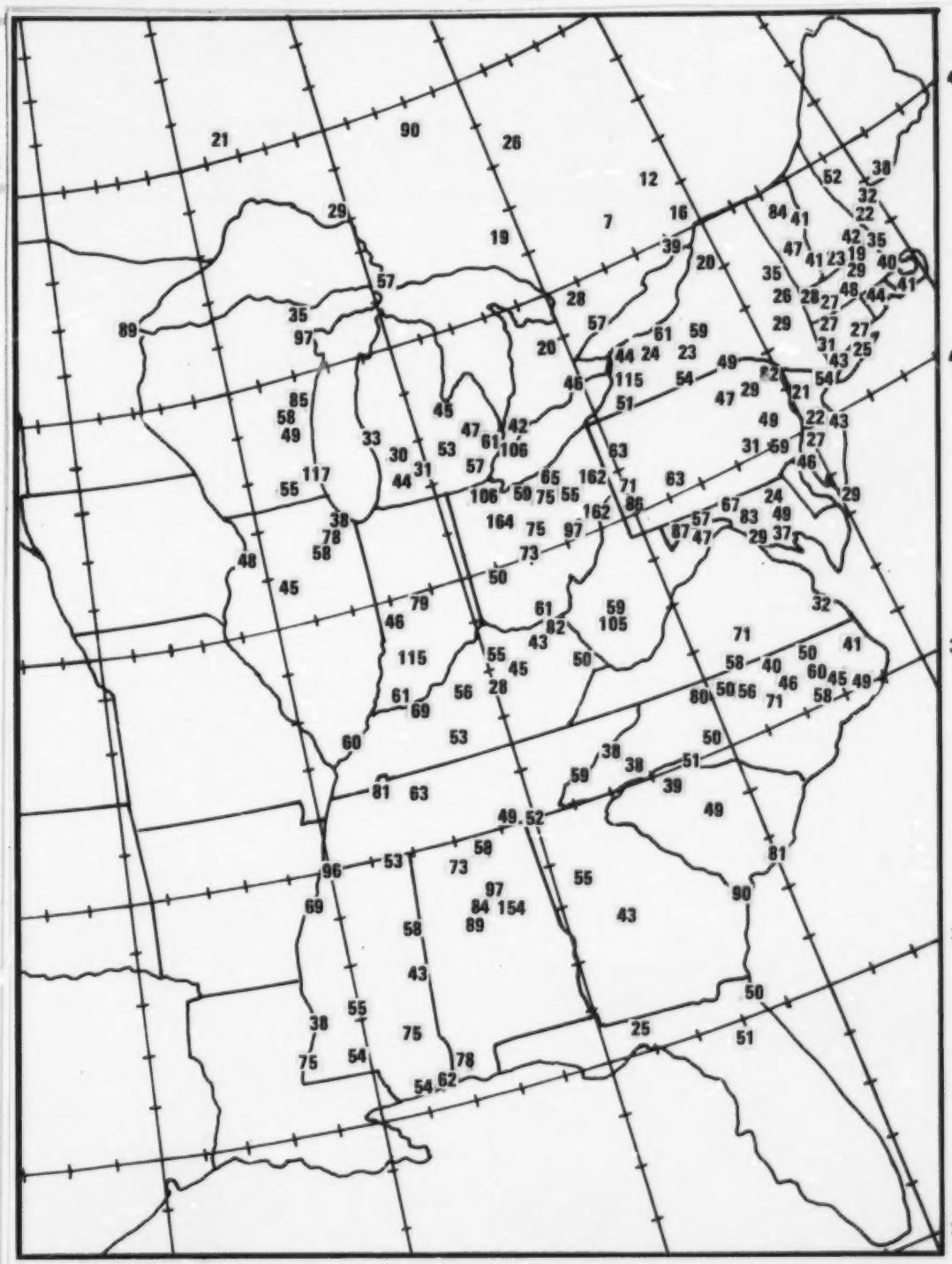

Figure 4. Total suspended particulate concentrations ($\mu g/m^3$) August 16, 1976.

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the 13 days, 687 $\mu g/m^3$, occurred. The Asphaltum station was the only station showing a concentration in excess of the standard (260 $\mu g/m^3$) on this day, demonstrating that there can be isolated, localized high concentrations.

On August 18, data from 60 stations show concentrations that were generally the same as those on August 17. Asphaltum was the only site exceeding the standard (260 $\mu g/m^3$), reporting a concentration of 569 $\mu g/m^3$.

On August 19, using data from 50 stations, the concentrations were found to be about the same as on August 18 with the exception of Asphaltum and three sites in Ohio. The concentration in Asphaltum dropped to 125 $\mu g/m^3$ and the three Ohio sites had concentrations slightly in excess of 200 $\mu g/m^3$. There were no violations of the standard.

On August 20, 45 stations reported; only one station in the Canton-Ohio area showed a violation (272 $\mu g/m^3$). At the other stations, concentrations were very much like those of the day before.

There was practically no change from August 20 to August 21; the one station in the Canton-Akron area continued to show a violation of the standard.

The TSP distribution of concentrations on the last day of the Korshover stagnation period, August 22, is depicted in Figure 5. Concentrations exceeding 200 $\mu g/m^3$ occurred over southeastern Michigan, eastern Ohio and northeastern Indiana. Excluding those areas, the average concentration for the rest of the area under stagnation conditions (Figure 1) was approximately 100 $\mu g/m^3$. Thus, only a very small part of the area under stagnation conditions experienced high TSP concentrations or a buildup in concentrations during the seven-day period. In addition, the areas of restricted visibility of August 21 and 22, shown in Figure 2, extended far beyond the areas with high TSP concentrations. Therefore, the areas with restricted visibility and the areas with high TSP concentrations did not coincide.

On August 23, the day after the passage of the front (see Figure 2) ended the Korshover-determined stagnation, the data from 45 stations indicated that the front had relatively little effect on the TSP concentrations;

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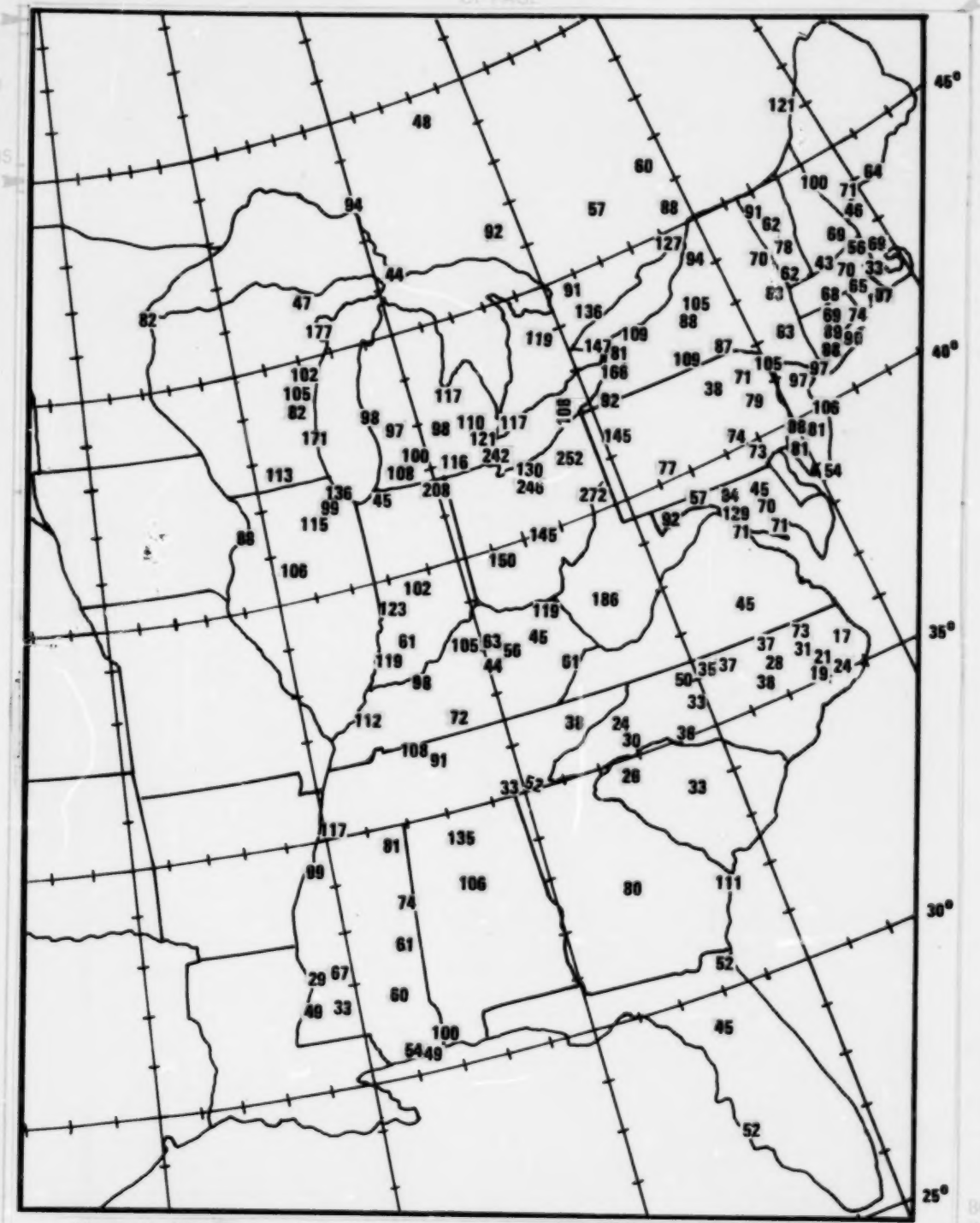

Figure 5. Total suspended particulate concentrations ($\mu g/m^3$) August 22, 1976.

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the concentrations were generally as high as or higher than they were on August 22. In addition, the area of restricted visibility was still much larger than the area with high TSP concentrations.

From August 23 to 27, 40 to 55 stations recorded concentrations each day. These data showed very little change in TSP concentrations during this period. Violations of the standard occurred on certain days at isolated locations such as Chicago, Asphaltum and the Canton-Akron area; but, no broad areas showed high concentrations.

The distribution of TSP concentrations on August 28 is shown in Figure 6. Comparing the area of restricted visibility shown in Figure 2 to the distribution of these TSP concentrations reveals that the area of restricted visibility was not marked by high TSP concentrations. Overall, there did not appear to be spatial agreement between areas of restricted visibility and areas of high TSP concentrations.

SULFUR DIOXIDE AND CARBON MONOXIDE

Sulfur dioxide and carbon monoxide are considered jointly because the analysis of the daily data show similar results. At no time was there a violation of the NAAQS for either pollutant and there were no progressive increases in concentration of either pollutant at any station. During August 16 to 28, there were 2959 station-days of data among the 229 stations monitoring sulfur dioxide in the eastern United States and only 14 station-days showed average daily concentrations exceeding 0.07 ppm (50 percent of the standard). The carbon monoxide data based on 1206 station-days for 91 stations, showed there were only three station-days when a concentration exceeded 50 percent of the standard during August 16 to 28.

In spite of the stagnation, no groups of stations showed high concentrations of sulfur dioxide or carbon monoxide on any day. In addition, there was no indication that there were high concentrations of sulfur dioxide or carbon monoxide in the areas of restricted visibility observed from August 21 to 28 (see Figure 2).

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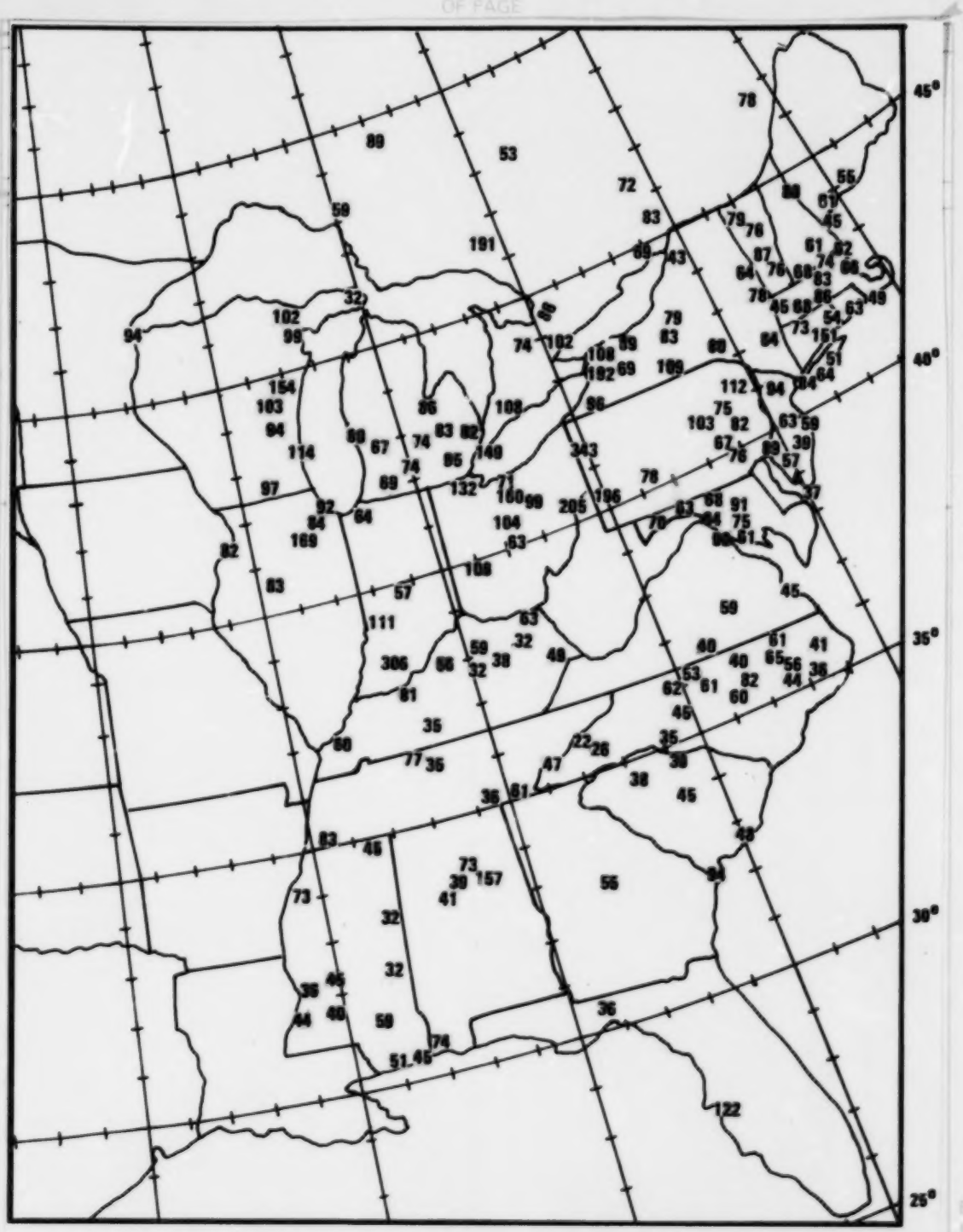

Figure 6. Total suspended particulate concentrations ($\mu g/m^3$) August 28, 1976.

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OZONE

The ozone data for August 16 to 28 for most states are adequate. The ozone data for Pennsylvania, West Virginia, and Virginia are limited. Since these states were in the areas affected by stagnation (Figure 1 and restricted visibility (Figure 2), the ozone analyses are also limited.

In evaluating the ozone data, values equal to or exceeding the old standard (8 pphm), but less then the new standard (12 pphm) are labeled moderate. Those concentrations of 12 pphm or more are called high. The distribution of ozone concentrations is compared to Figure 1 when reference is made to stagnation and to Figure 2 when restricted visibility is discussed.

The data for the first day of stagnation, August 16, shown in Figure 7 indicate that ozone concentrations over the eastern United States were generally low. Only a few, small, isolated areas experienced moderate or high concentrations.

On August 17, no multi-state areas had moderate or high concentrations (Figure 8). As noted in the discussion of stagnation, the slow air movement early in the episode occurred in the southwestern areas where most of the moderate concentrations of ozone were first recorded.

On August 18, the entire western area extending from Louisiana in the south to Wisconsin and Michigan in the north had moderate or high concentrations (Figure 9). In spite of this, areas in Ohio and parts of New York that were under stagnating conditions did not have moderate or high concentrations. Smaller areas of high concentrations of ozone were observed in an elongated area extending from Chicago to Milwaukee, near Detroit, and near Philadelphia.

On the fourth day of the stagnation episode, August 19, there was one broad area with moderate or high concentrations (Figure 10). This area extended from Wisconsin and Illinois in the west to New York in the east and thence southwestward to Louisiana. Low concentrations were observed over New England and the coastal area to the south and an area extending in an east-west direction across southern Illinois, Indiana,

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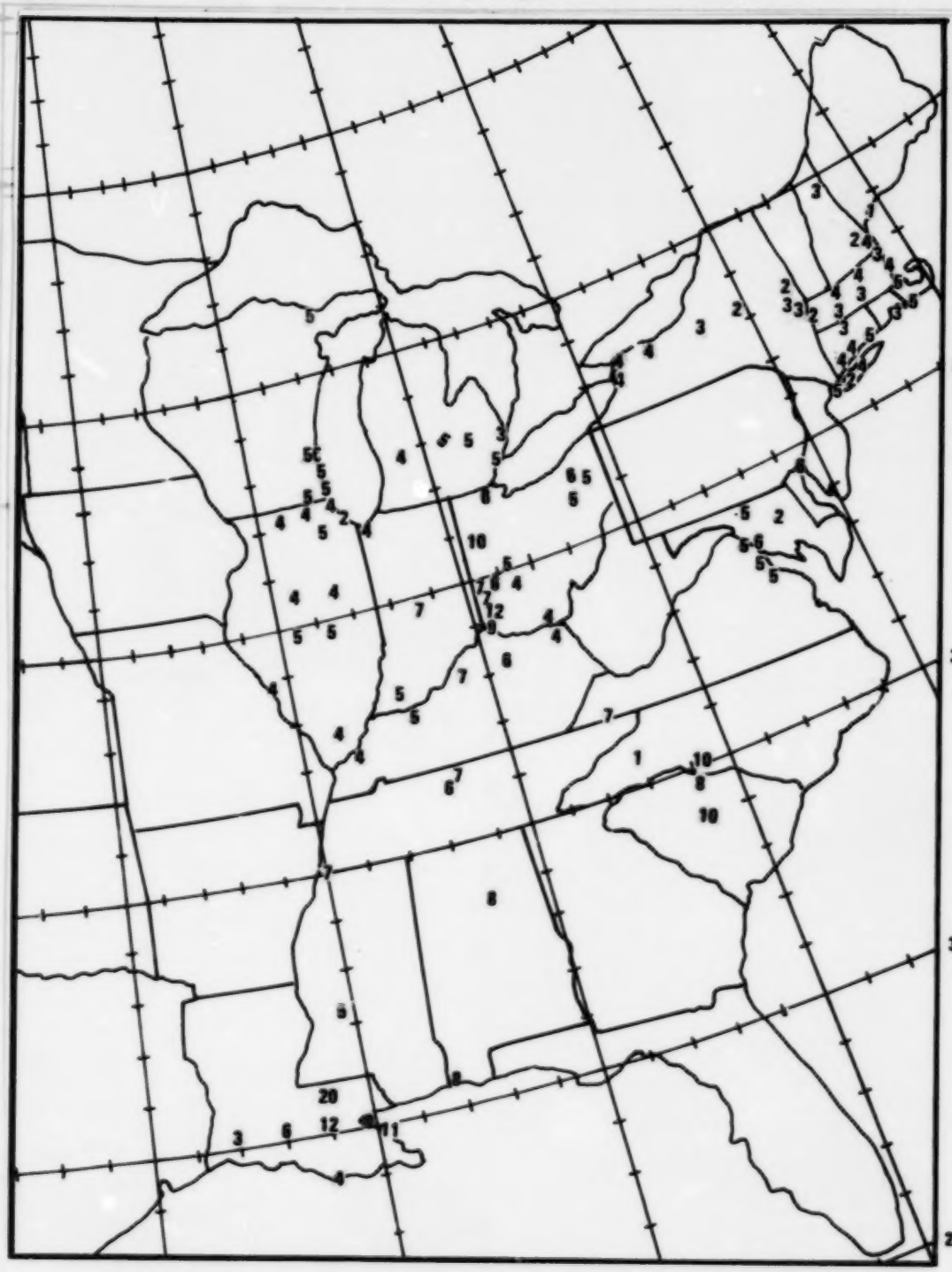

Figure 7. Maximum hourly ozone concentrations (pphm) August 16,1976.

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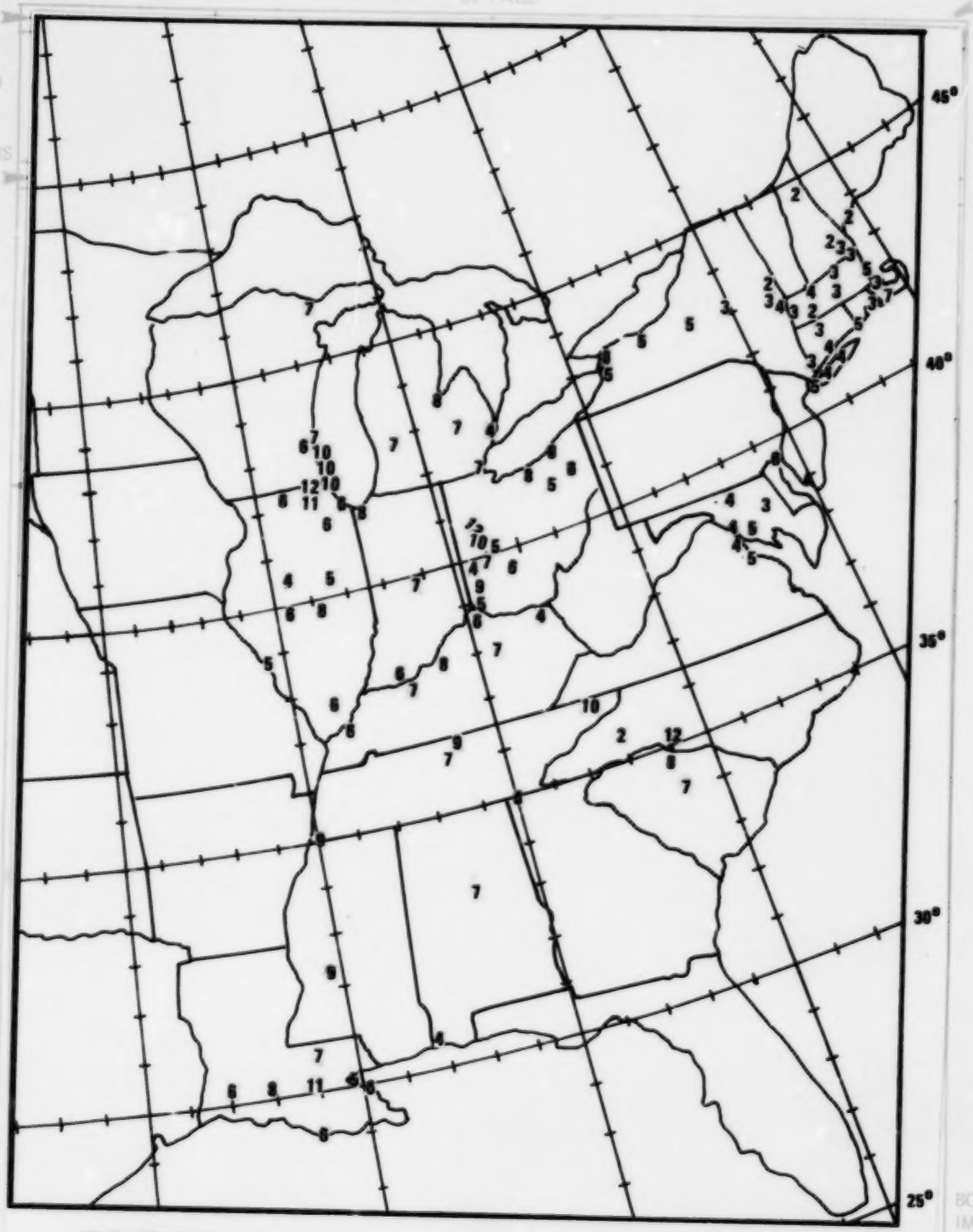

Figure 8. Maximum hourly ozone concentrations (pphm) August 17, 1976.

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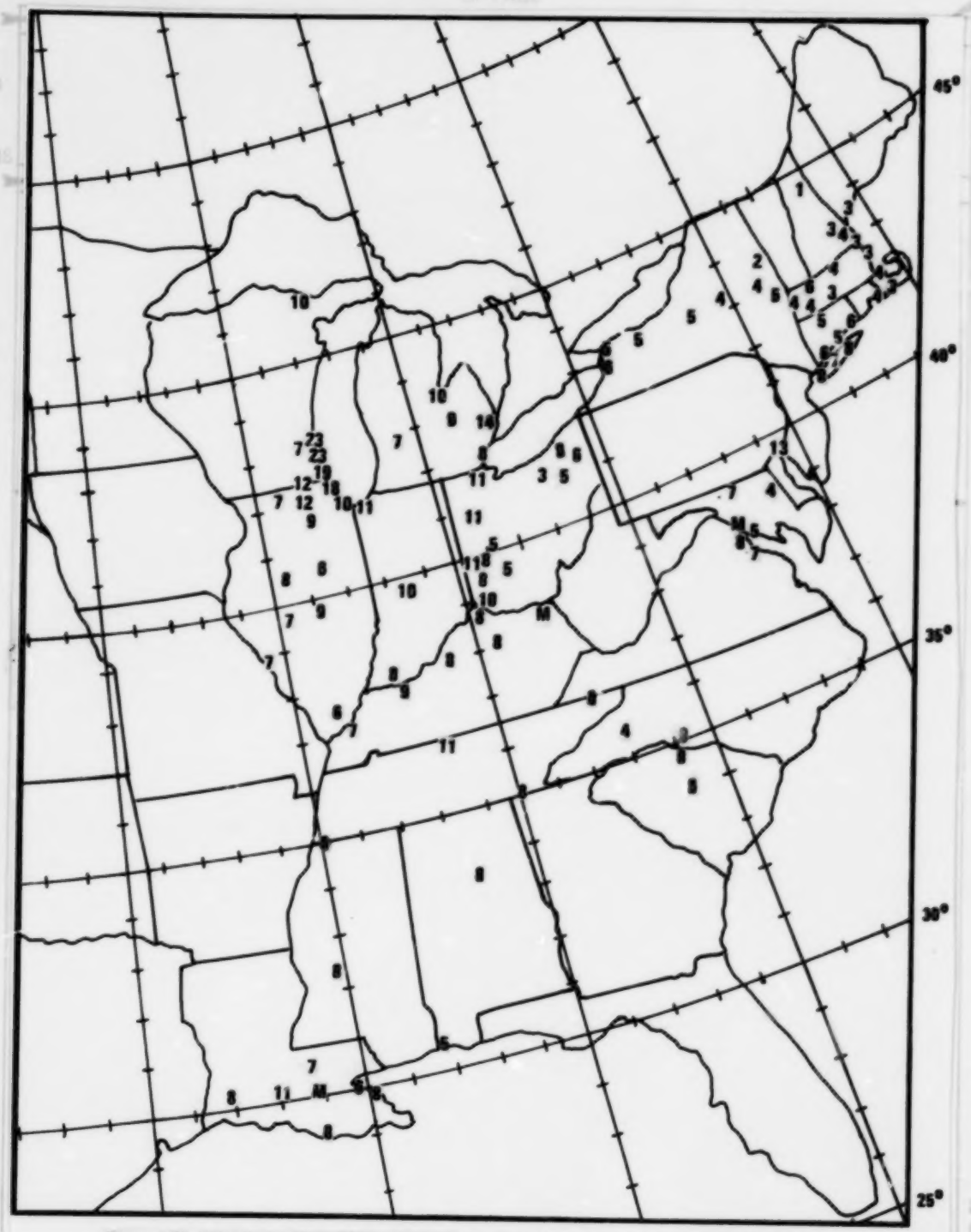

Figure 9. Maximum hourly ozone concentrations (pphm) August 18, 1976.

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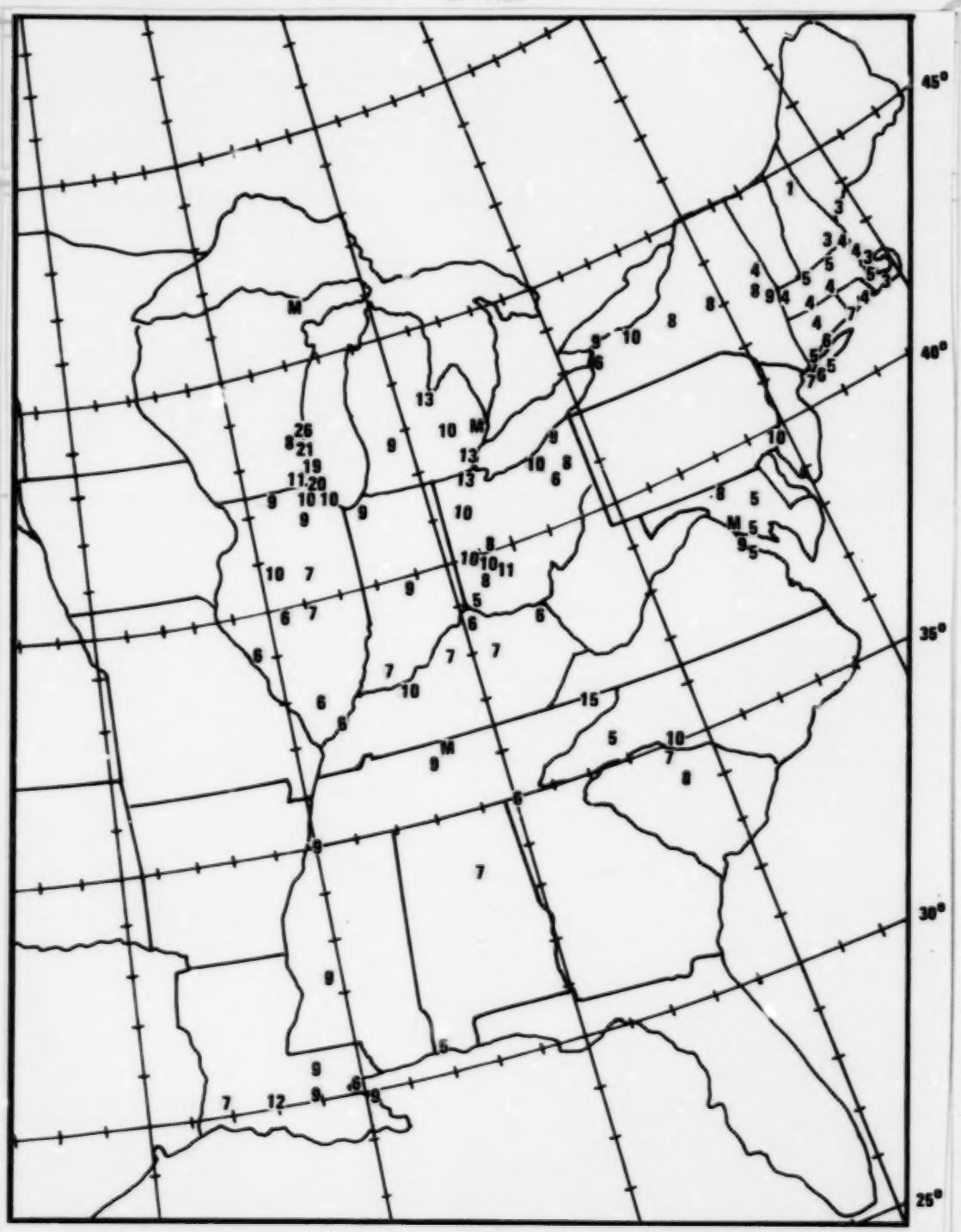

Figure 10. Maximum hourly ozone concentrations (pphm) August 19,1976.

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and Ohio. Overall, moderate concentrations of ozone were observed on some days when stagnation was not indicated and some sites within the stagnation area had low concentrations of ozone. Thus, there was poor spatial agreement between the stagnation area and areas with moderate and high ozone concentrations.

On August 20, as shown in Figure 11, the area of moderate and high concentrations covered about two-thirds of the eastern United States; the only areas with low concentrations were the southeast, an area around Paducah, Kentucky, and most of New England (Figure 1). Three separate, multi-state areas had high concentrations and each was associated with a source area of ozone precursors[15]: 1) Chicago and along the coast of Wisconsin; 2) the Toledo-Detroit-Cleveland area; and 3) the Atlantic coast area from Philadelphia to just south of Boston. On this day the boundaries of the areas of stagnation were similar to the boundaries of the area with moderate and high ozone concentrations. Although all of the sites in the northern tier of states, exclusive of New England, were showing moderate and high ozone concentrations, there was no extensive area of reduced visibility.

On August 21, shown in Figure 12, the ozone concentration pattern was similar to that of August 20 (Figure 12). The three discrete areas with high concentrations (maximum hourly concentrations are shown and typically at night all areas showed low concentrations). More than half of the stations in the area of restricted visibility had high ozone concentrations and the remainder had moderate concentrations. On this day, there was limited coincidence of the areas of moderate and high ozone concentrations, the areas of stagnation, and the areas of restricted visiblity.

On August 22, as shown in Figure 13, the ozone concentration pattern was similar to that of August 21. This similarity extended to the reappearance of the three separate multi-state areas with high concentrations. The spatial agreement among the areas of moderate and high concentrations, areas of stagnation, and areas of restricted visibility was again limited.

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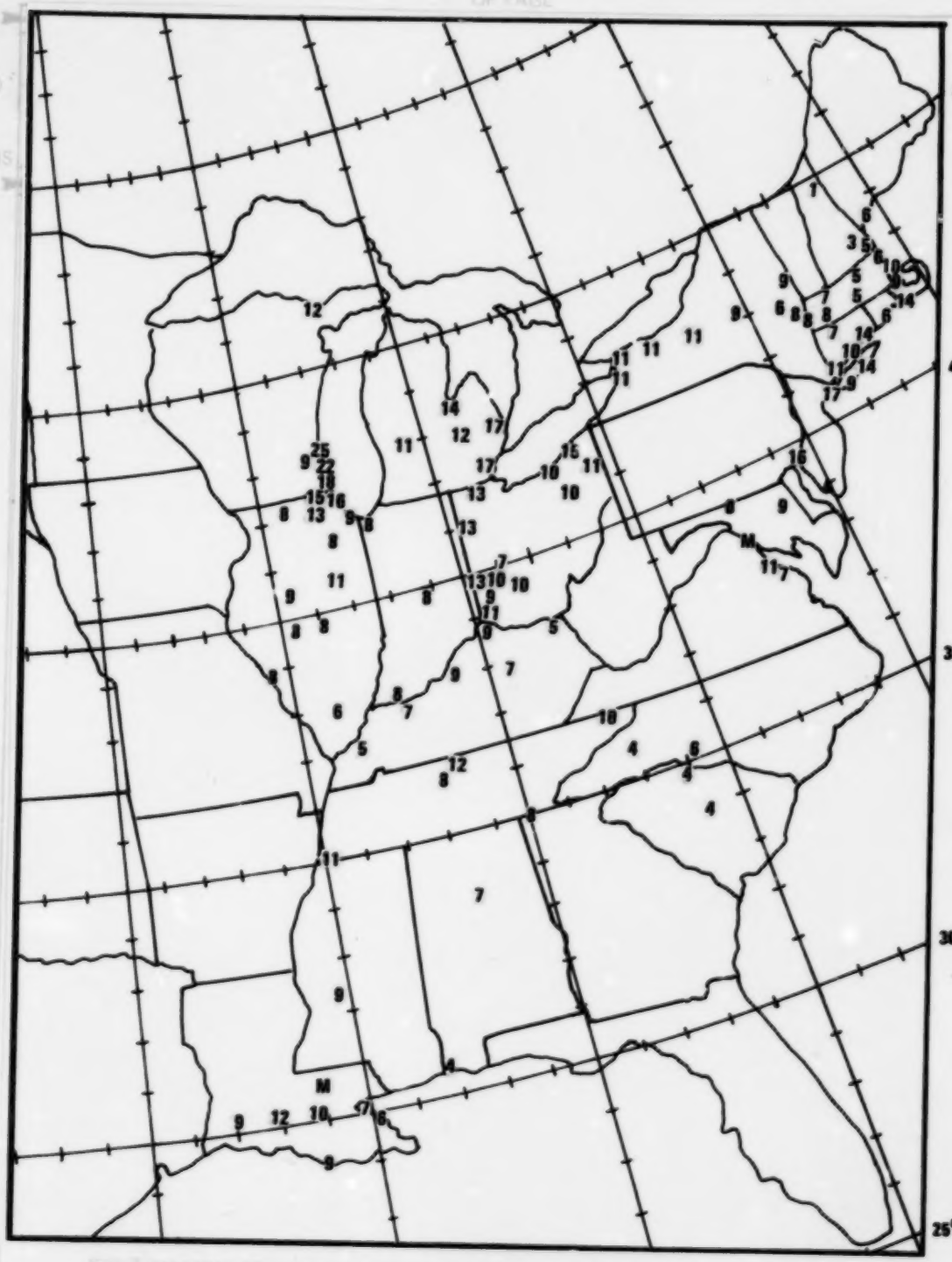

Figure 11. Maximum hourly ozone concentrations (pphm) August 20.1976.

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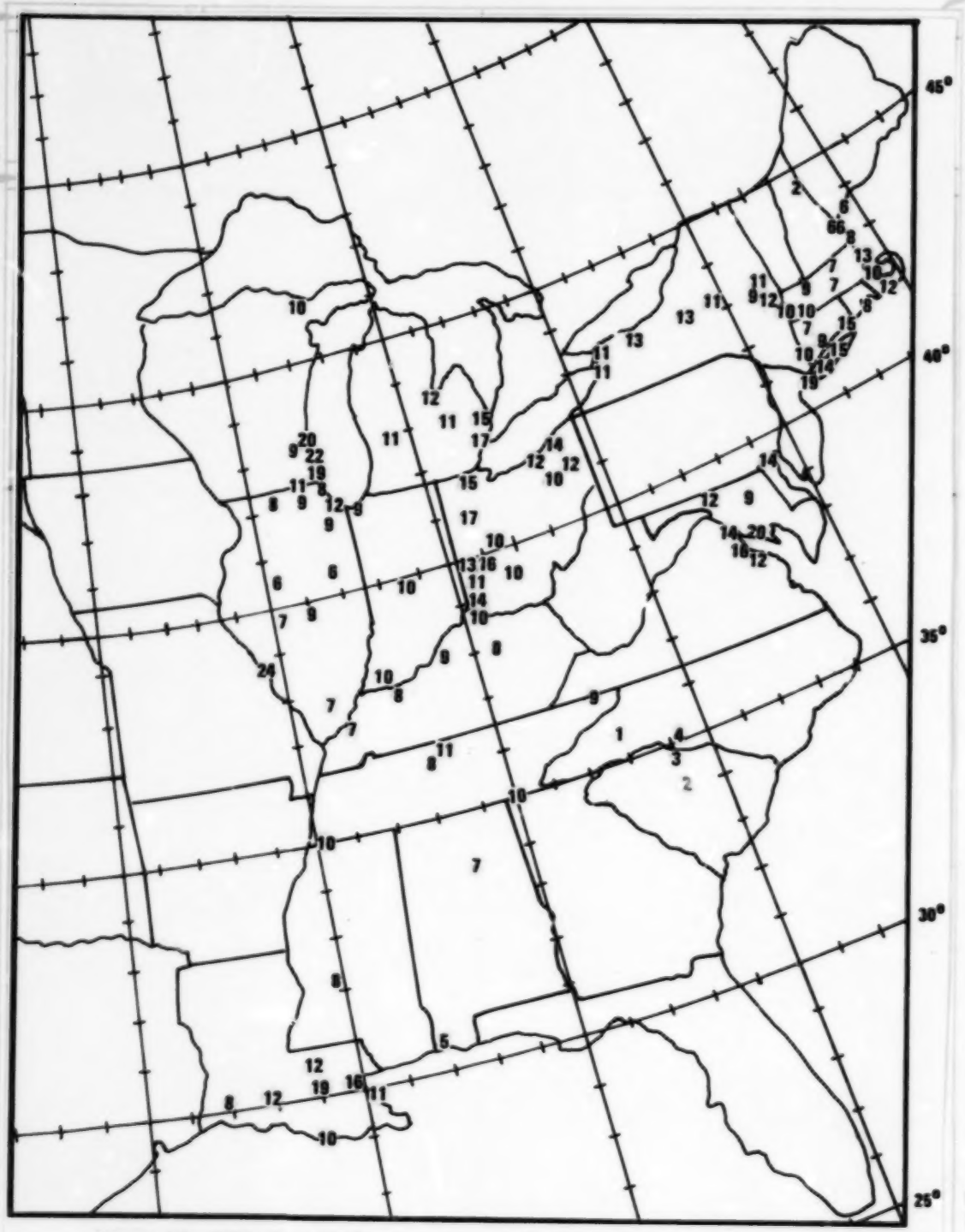

Figure 12. Maximum hourly ozone concentrations (pphm) August 21,1976.

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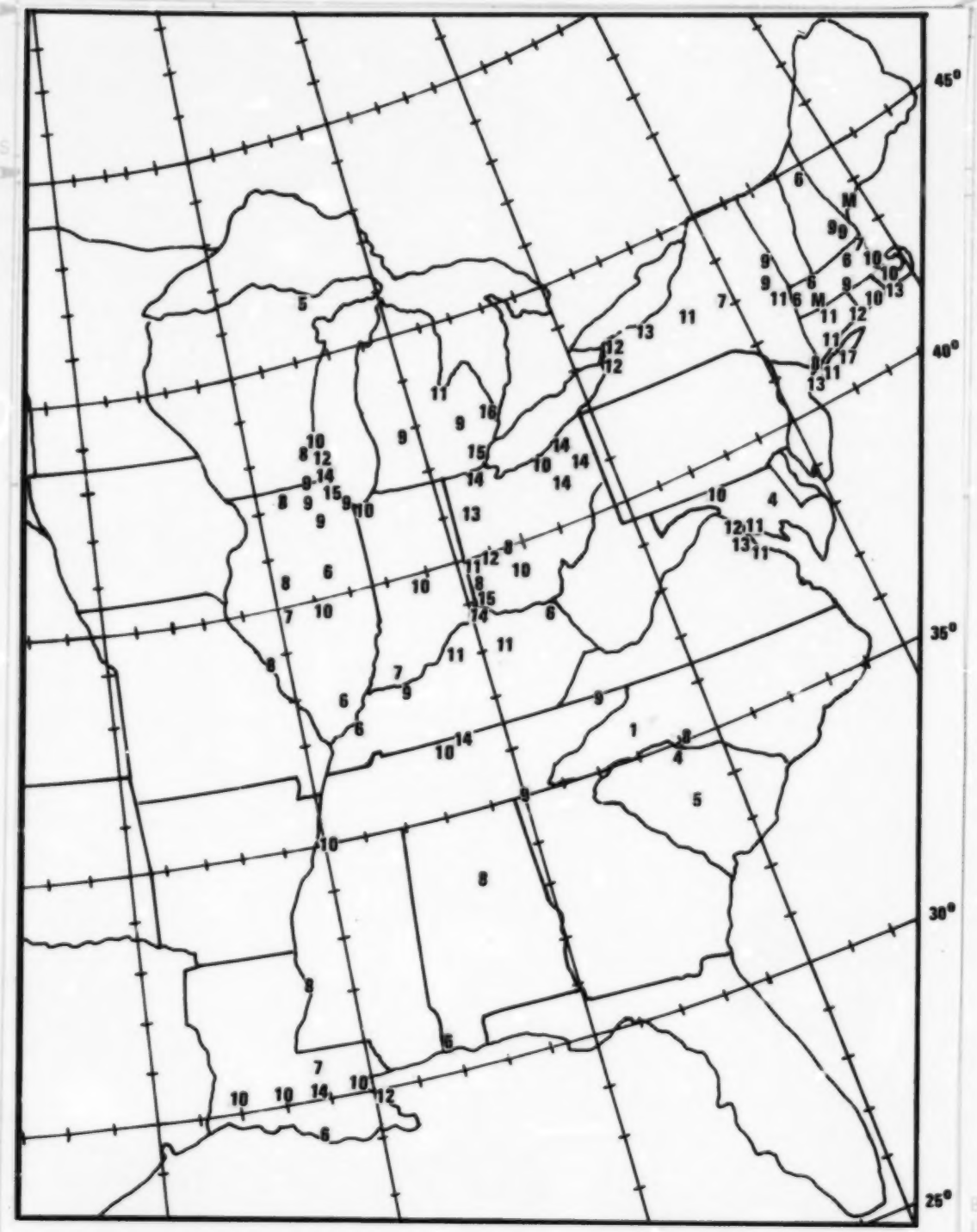

Figure 13. Maximum hourly ozone concentrations (pphm) August 22,1976.

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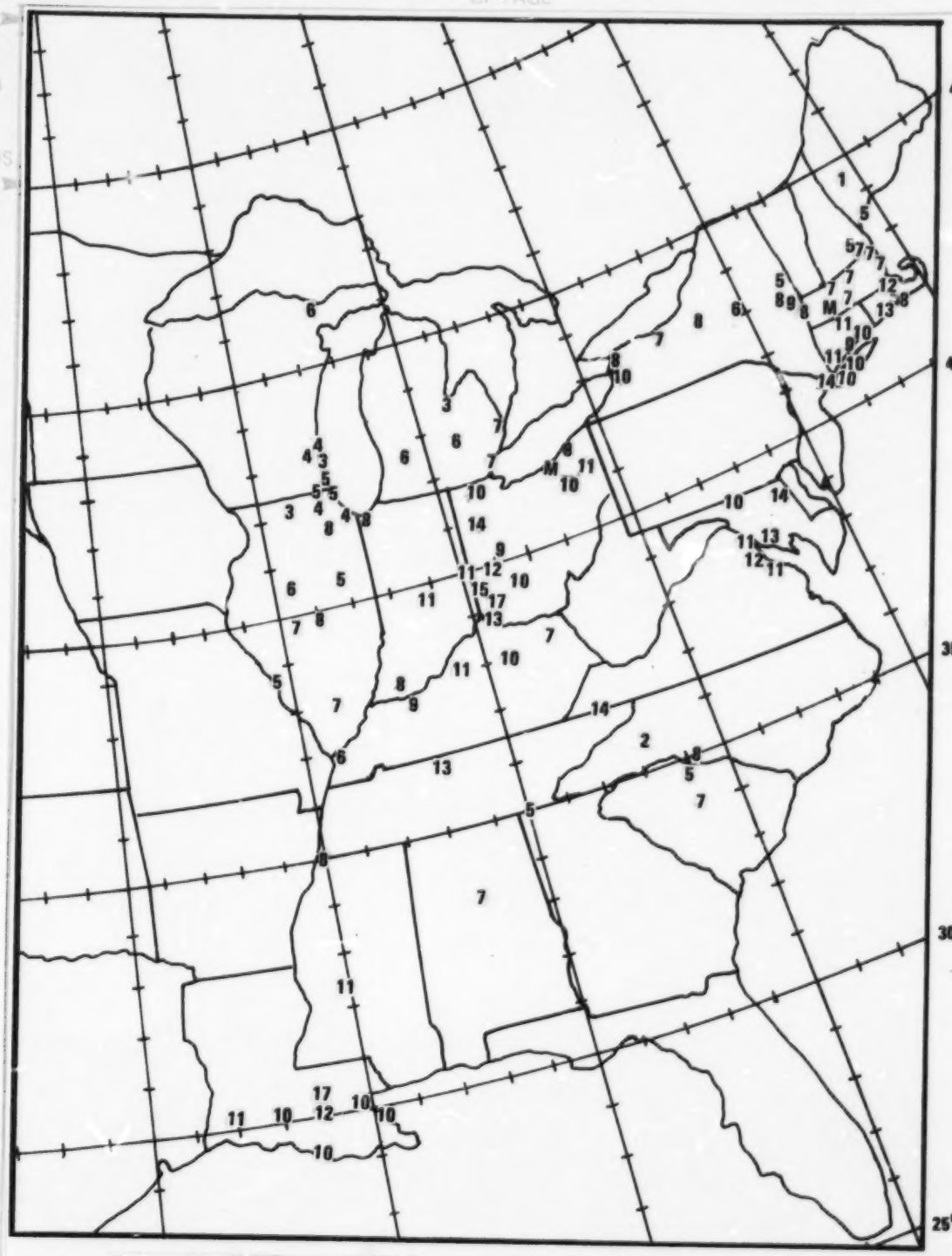

Figure 14. Maximum hourly ozone concentrations (pphm) August 23, 1976.

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The ozone concentrations on August 23, shown in Figure 14, were lowered in the northern tier of states by the frontal activity of that day (see Figure 2). In addition, the western area of high concentrations was eliminated and the multi-state area centered over western Ohio was reduced in size. In other areas the changes from August 22 to 23 were minor. Thus, the passage of the front, which ended the stagnation episode according to the Korshover analysis, reduced or eliminated the moderate and high concentrations at less than half of the sites in the area shown in the August 22 analysis. On this day the agreement between the area of restricted visibilities and the area of moderate and high concentrations was poor; the area of restricted visibility had ozone concentrations ranging from low to high.

The ozone concentrations on August 24, shown in Figure 15, show that the area with high concentrations, which was centered over western Ohio, expanded while the east coast area decreased in size. The change in the size of the area with moderate concentrations was minor. In the southwest corner, high concentrations which had been seen every day in Louisiana since August 19 expanded into Mississippi. Thus, the moderate ozone concentrations were still prevailing over the area long after the Korshover-designated stagnation ended and the area of restricted visibility had ozone concentrations ranging from low to high.

The changes in ozone concentrations from August 24 to August 25 was rather marked. On the 25th, shown in Figure 16, there were larger separate areas with moderate and high ozone concentrations. These areas were not symmetrical and most were elongated in a general north-south or northeast-southwest direction. Thus, several days after the passage of the front most sites still had moderate and high concentrations of ozone. Over the area of restricted visibility, as one progressed from west to east, areas of moderate and high concentrations alternated with areas of low concentrations.

By August 26, as shown in Figure 17, only about half of the stations had moderate and high concentrations. While most of the moderate and high concentrations occurred in the area of restricted visibility, many of the sites in that area had low concentrations of ozone.

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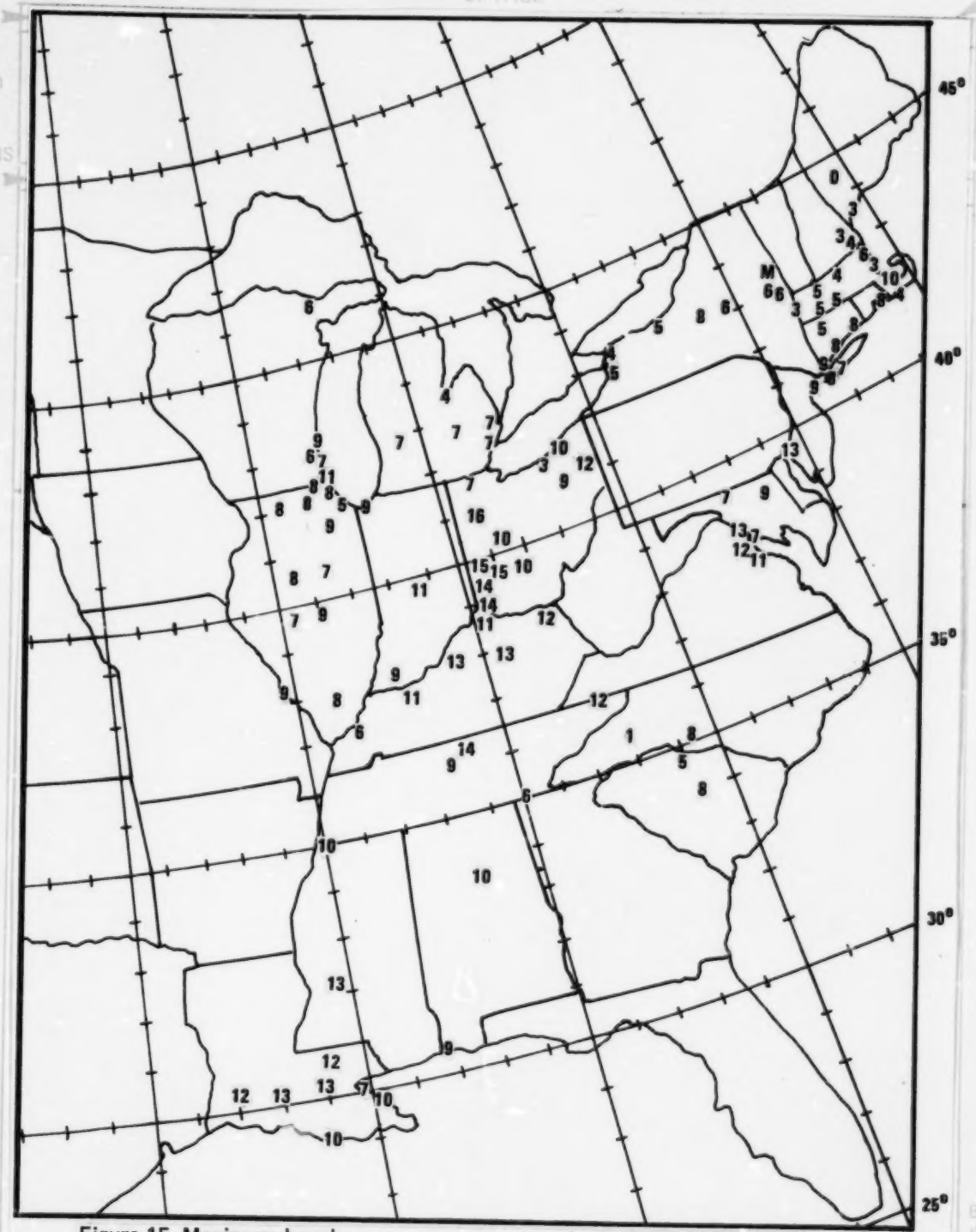

Figure 15. Maximum hourly ozone concentrations (pphm) August 24, 1976.

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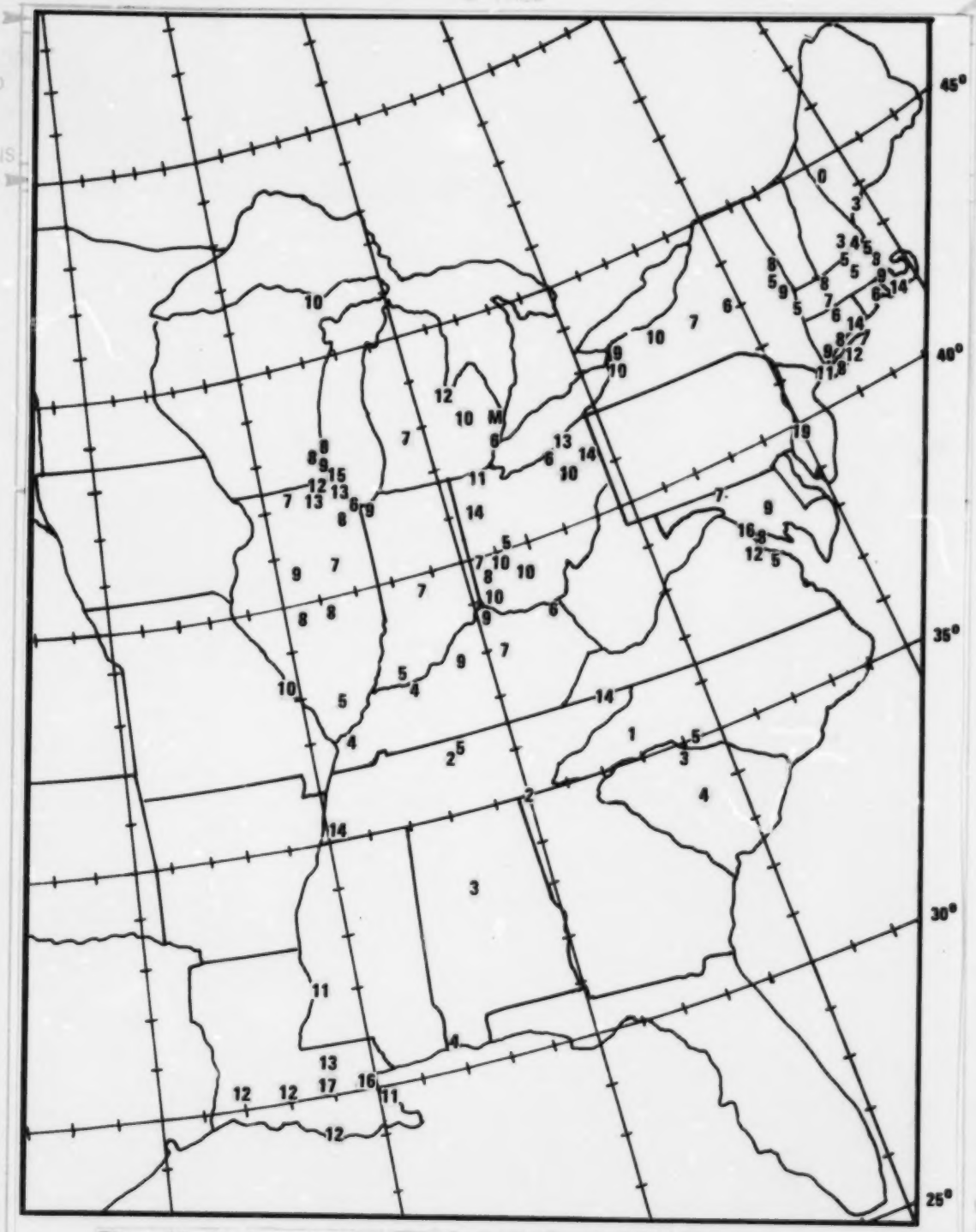

Figure 16. Maximum hourly ozone concentrations (pphm) August 25, 1976.

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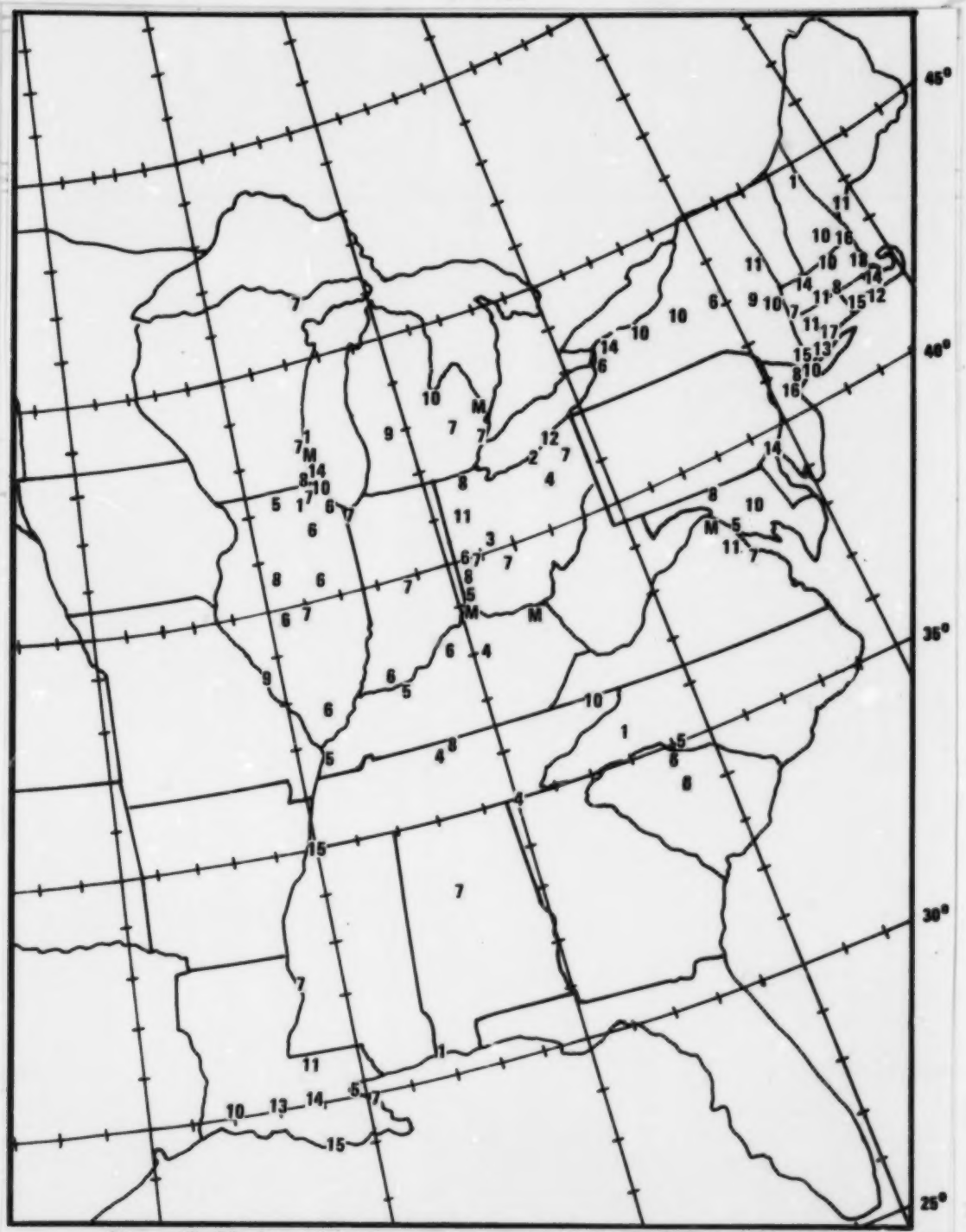

Figure 17. Maximum hourly ozone concentrations (pphm) August 26, 1976.

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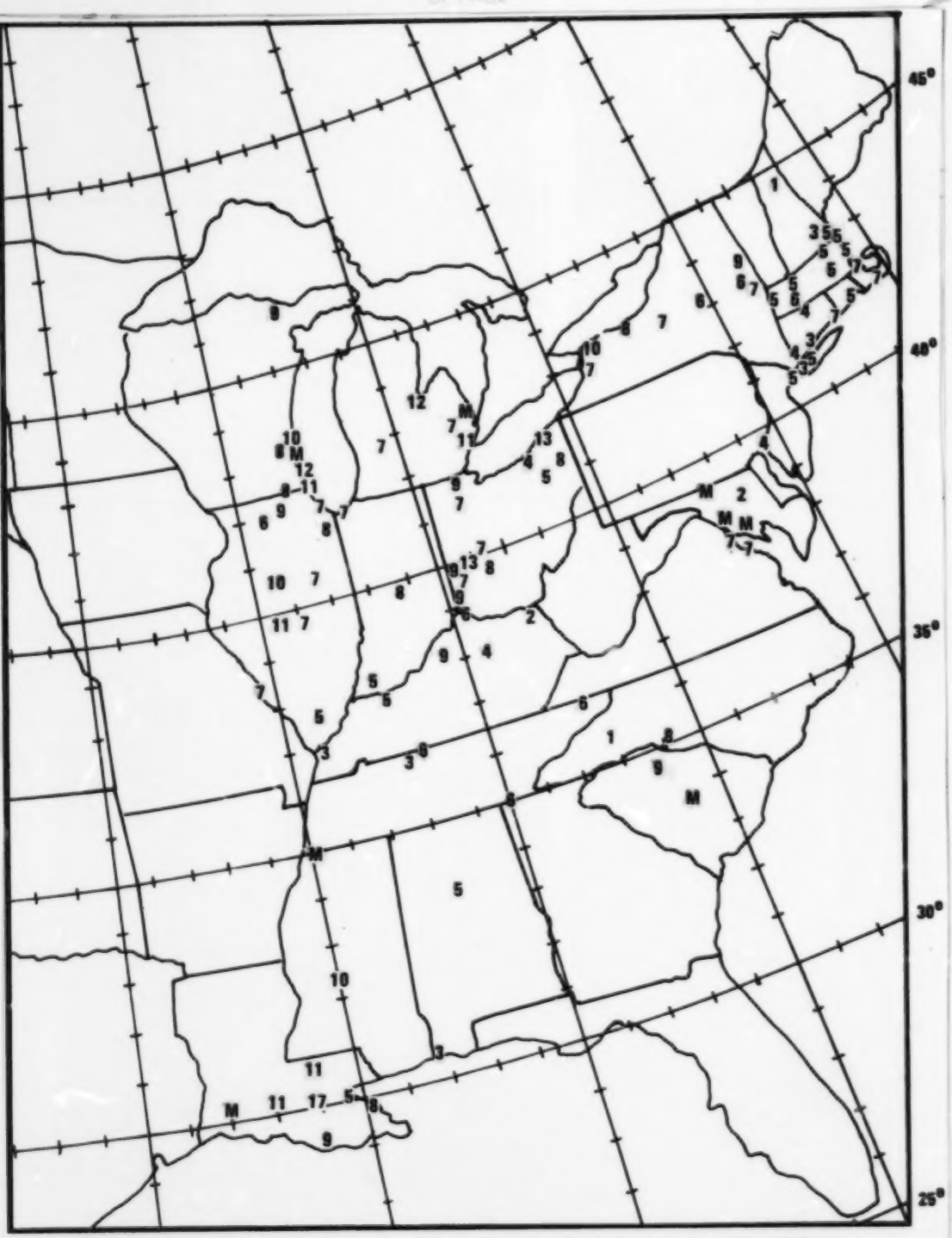

Figure 18. Maximum hourly ozone concentrations (pphm) August 27, 1976.

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On August 27, approximately one-third of the sites spread throughout the eastern United States had moderate or high ozone concentrations (Figure 18). Only about half of the sites in the area with restricted visibility had moderate or high ozone concentrations.

On August 28, the number of sites with moderate and high concentrations was about the same as on August 27, but the number decreased in the northwest and increased in the northeast (Figure 19).

Thus the ozone concentrations increased for several days as the stagnating conditions persisted after the frontal passage of August 23.

The spatial agreement between areas of restricted visibility and areas of moderate and high concentrations was generally poor. There were large areas where moderate and high ozone concentrations occurred before there was restricted visibility. In addition, in the areas with restricted visibility, the ozone concentrations on most days ranged from low to high.

Ozone data for southeastern Canada were not obtainable prior to the completion of the figures showing the ozone distributions. Ozone data for a nineteen-station network for extreme southern Ontario were received later; but because these data were for a very limited area, the ozone figures were not revised. The Canadian data showed that the ozone concentrations increased to moderate and high values during the period August 16 to 22, were lowered with the frontal passage of August 23, and were never high thereafter. These data indicated that the Korshover technique properly designated the stagnation period with respect to ozone concentrations for this small area.

SULFATES

The sulfate data for August 16 to 28 for most states is far from adequate. The majority of states in the eastern United States had data for August 16 and 28 only. Ohio and Pennsylvania, which were in the center of the stagnation area and of the area of restricted visibility, had state-wide data for August 22, as well as August 16 and 28. There were sulfate data collected for almost every day for a dozen or more

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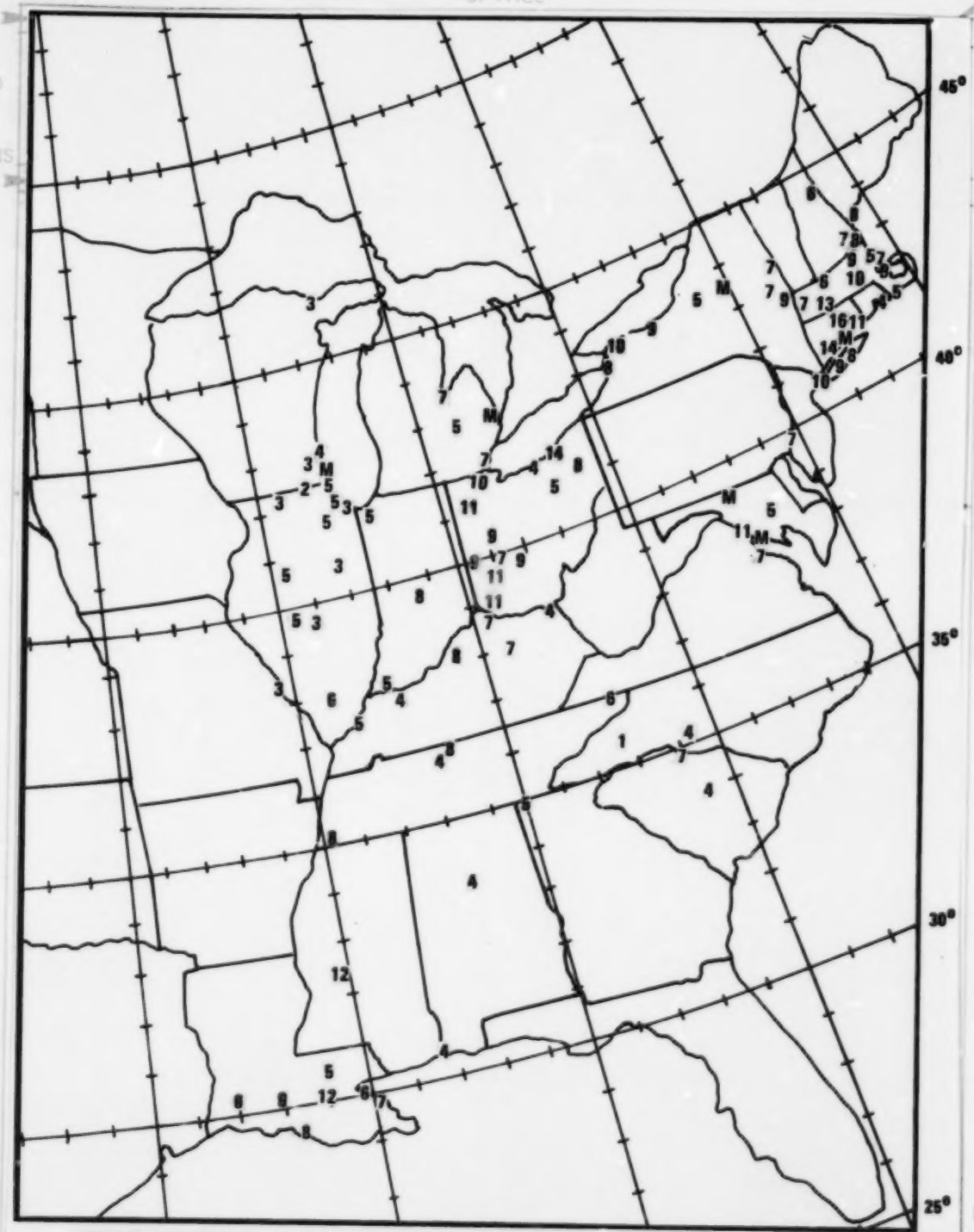

Figure 19. Maximum hourly ozone concentrations (pphm) August 28, 1976.

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sites in southern Canada. Since that area formed the northern part of the stagnation area and restricted visibility area, these Canadian data are a major part of this sulfate analysis.

In evaluating the sulfate data, concentrations of 10 μg/m³ or more are labelled high. The distribution of sulfate concentrations is compared to Figure 1 when reference is made to stagnation and to Figure 2 when restricted visibility is discussed.

Abundant sulfate data were collected on August 16, the first day of the stagnation period. The spatial distribution of the concentrations of sulfate is shown in Figure 20. A broad area extending across the middle of the country had concentrations exceeding 10 μg/m³. Most of this area with high concentrations was within or very close to the stagnation area.

The sulfate data for August 17 to 21 are from Canadian sources only and are shown in Figure 21. On August 17, the concentrations over southern Canada were as low as they were on the previous day. On August 18, three sites in the west showed high concentrations. On August 19, with very limited data in the west, two stations in that area still showed high concentrations. On August 20, when more stations in the west reported, there was a very extensive area in southern Ontario with high concentrations. These Canadian data indicate that the sulfate concentrations increased markedly during the first days of stagnation and that the area of high concentrations increased in an eastward direction over time. In addition, the data for August 20 show that high sulfate concentrations existed over the area before restricted visibility was observed. The limited data for August 21 indicate that southern Ontario had sulfate concentrations similar to those observed on August 20.

On August 22, the last day of the Korshover stagnation period, the sulfate data were more abundant than they were on the 5 previous days and are shown in Figure 22. Concentrations exceeding 40 μg/m³ and even 50 μg/m³ occurred in many locations in Ohio and southern Ontario. High concentrations were observed in places as far away as southern New England and Montgomery, Alabama. Most of the areas marked by stagnation

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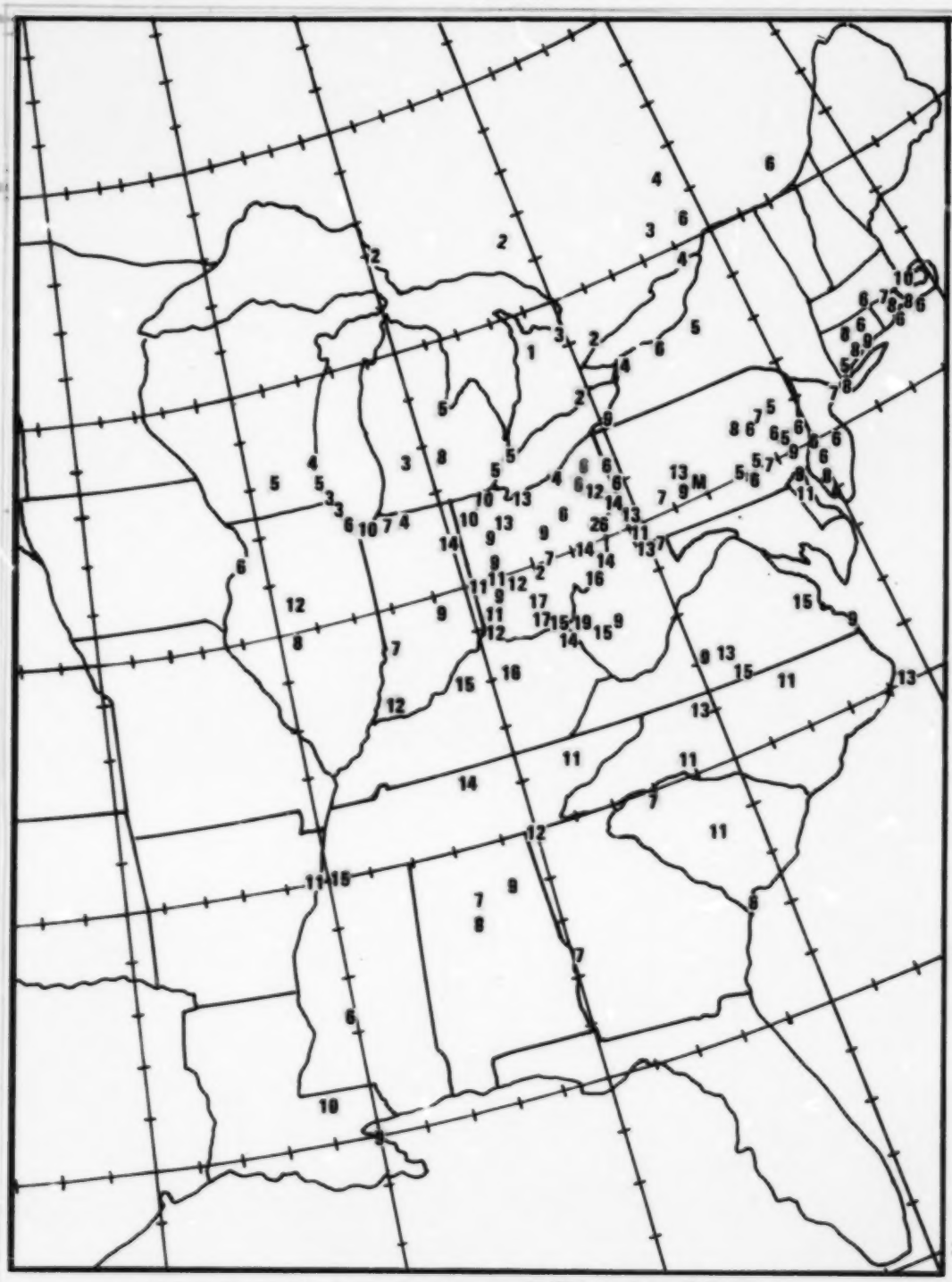

Figure 20. Sulfate concentrations ($\mu g/m^3$) August 16, 1976.

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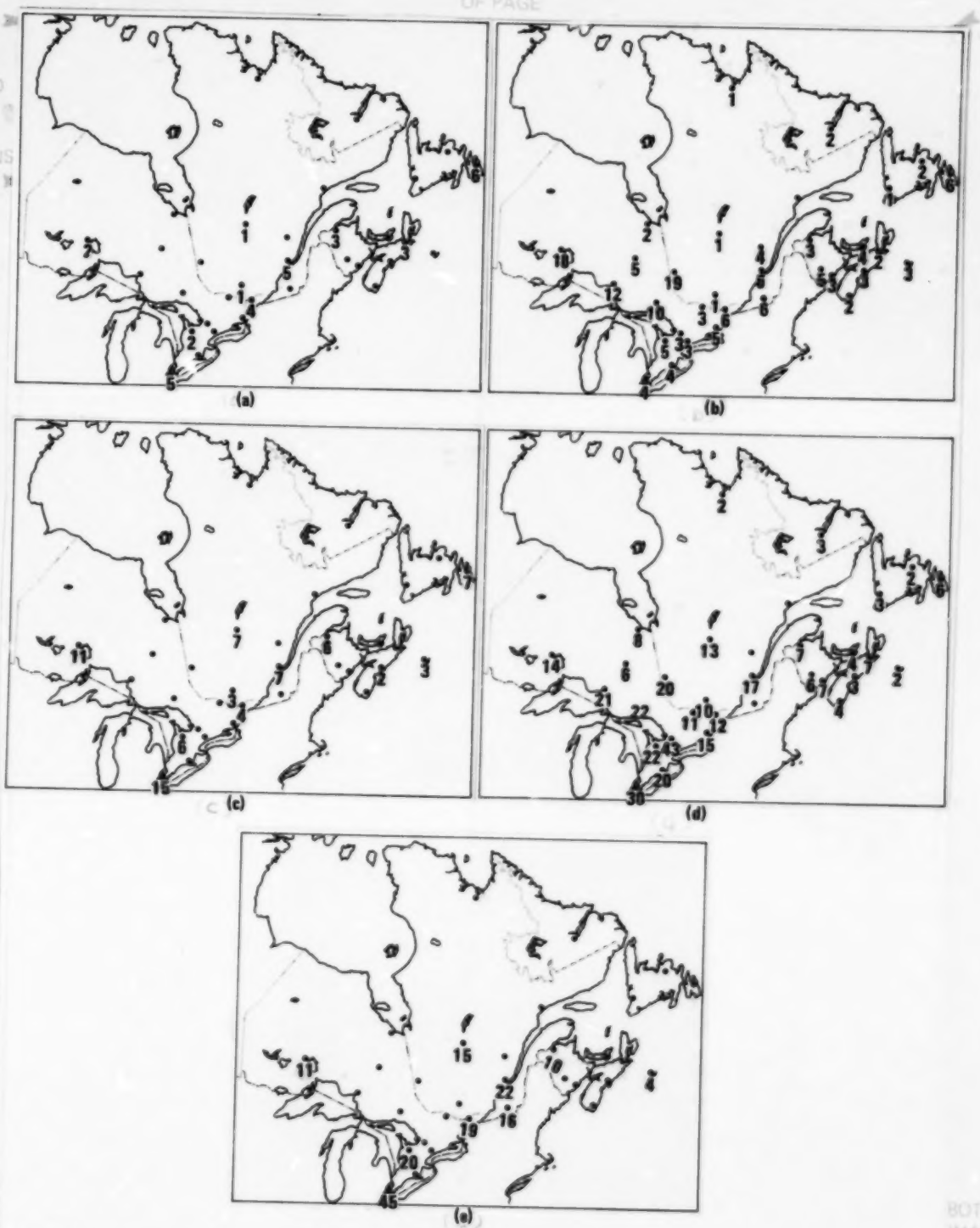

Figure 21. Sulfate concentrations ($\mu g/m^3$) southeastern Canada; (a) 8/17/76, (b) 8/18/76, (c) 8/19/76, (d) 8/20/76, (e) 8/21/76.

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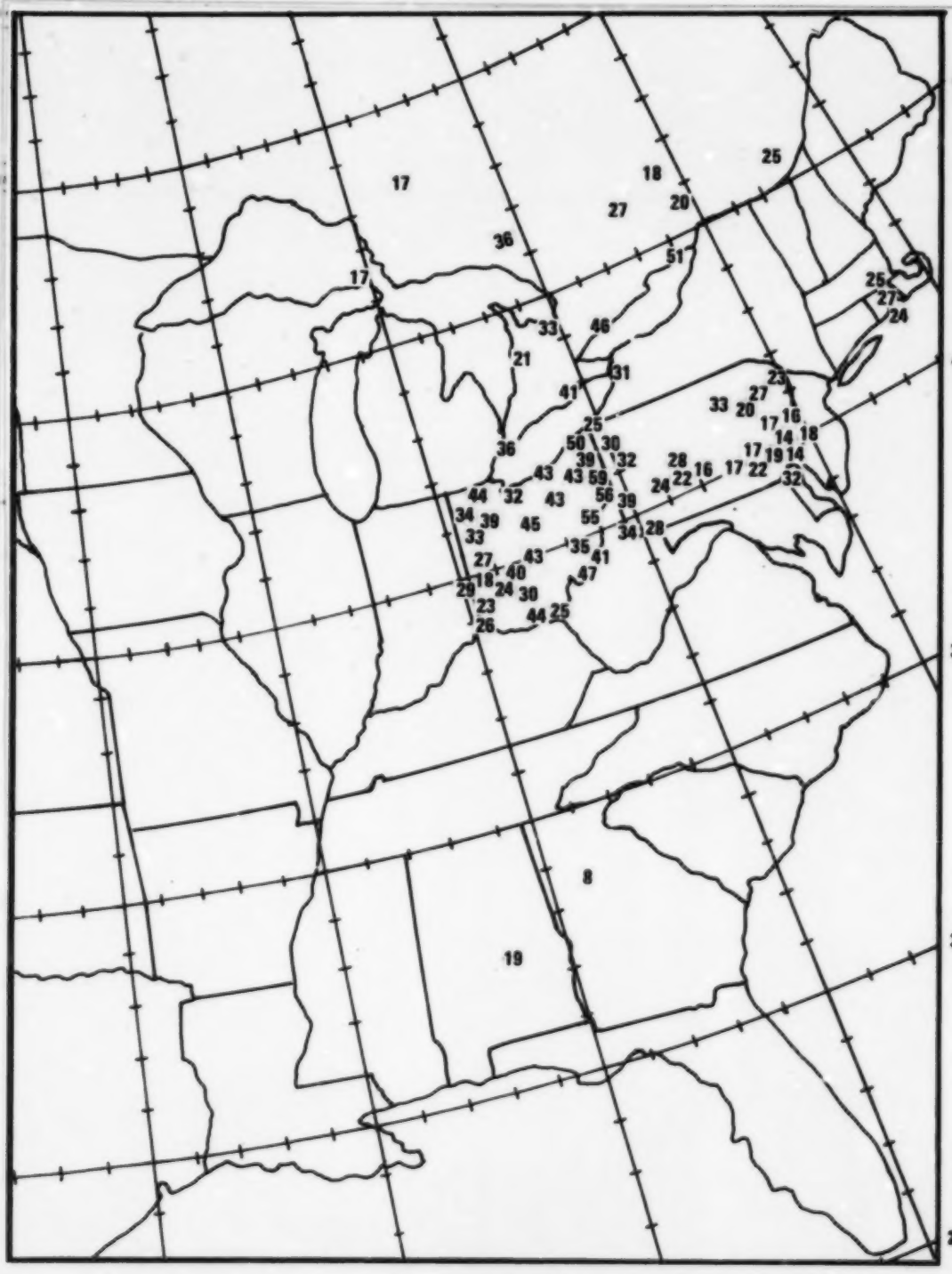

Figure 22. Sulfate concentrations ($\mu g/m^3$) August 22, 1976.

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and restricted visibility had very high sulfate concentrations on this day.

The sulfate data for August 23 to 27 were again limited to Canadian stations and are shown in Figure 23. On August 23, the concentrations for all but the eastern sites were much lower than they were on the previous day; the frontal passage did appear to lower the sulfate concentrations and improve the visibility in southern Canada. On August 24, the concentrations at all but one site were low. The area of restricted visibility was just below Canada; there was relatively good visibility over the Canadian area that had low sulfate concentrations. On August 25 using data from only 10 stations, the three westernmost stations showed high concentrations. The restricted visibility readings for August 25 did show poorer visibility moving into this western area. On August 26 the area of high sulfate concentrations was much more extensive and the restricted visibility area showed a comparable increase in size. On August 27, the area of high sulfate concentrations was displaced slightly to the east and the area of restricted visibility showed a similar displacement.

On August 28, the last day with a large area of restricted visibility, there was abundant sulfate data and the spatial distribution of these readings is shown in Figure 24. The one continuous area of high concentrations extended from eastern Kentucky and North Carolina in the south to southern Canada in the north and there were a few sites in the south with high concentrations. The area of restricted visibility was only half the size of the area with high concentrations; but, if a standard of 20 $\mu g/m^3$ is used instead of >9 $\mu g/m^3$, the area of restricted visibility coincided much more closely with the area of high sulfate concentrations.

The analyses of the limited amount of sulfate data show: 1) On the initial stagnation day, a large part of the area under stagnation conditions showed high concentrations; 2) although the Canadian stations did not show high sulfate concentrations on the first day or two of stagnation conditions, they did show high concentrations after several days; 3) there were high sulfate concentrations over southern Canada one day before the area recorded restrictions to visibility; 4) on August 22,

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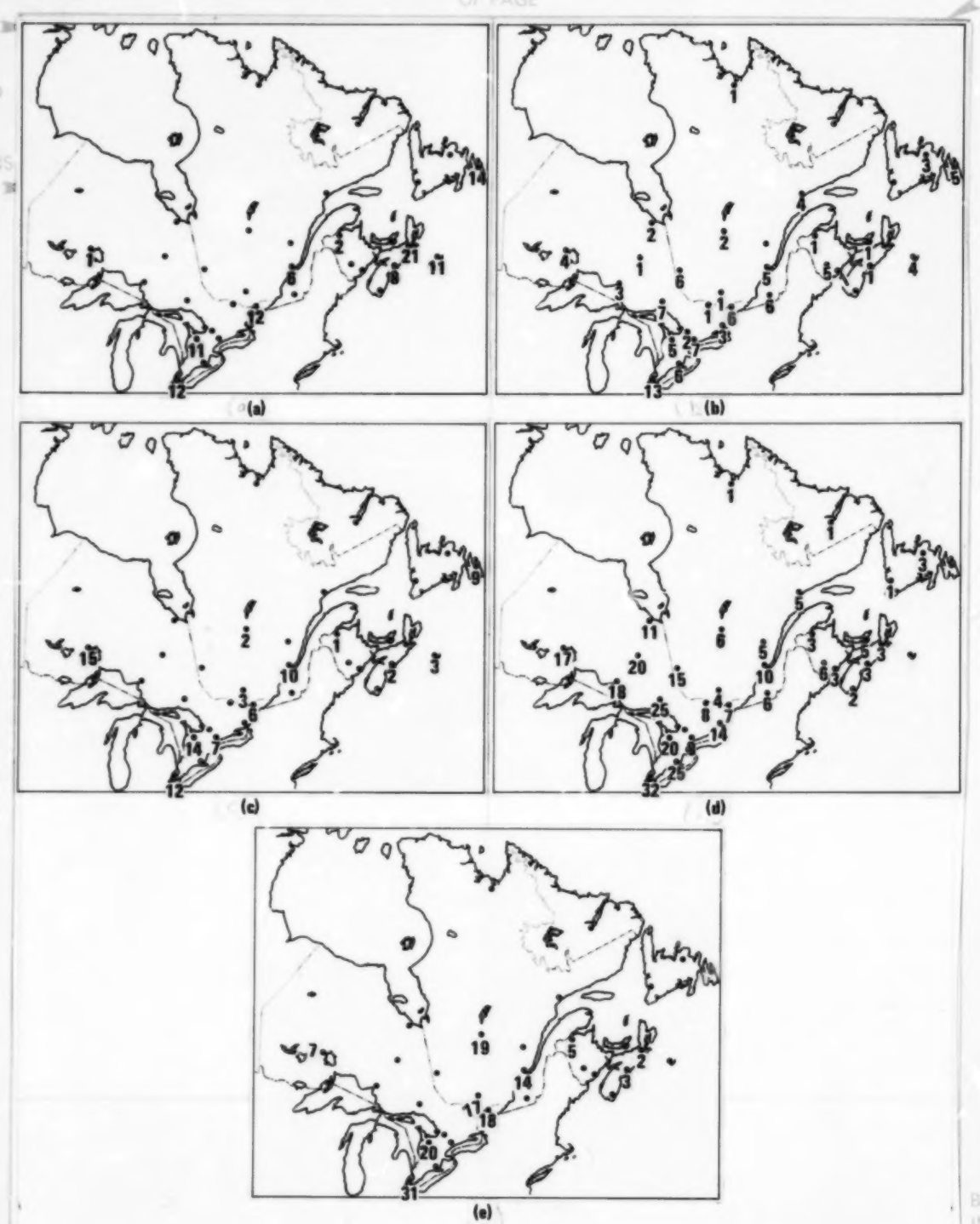

Figure 23. Sulfate concentrations ($\mu g/m^3$), southeastern Canada; (a) 8/23/76, (b) 8/24/76, (c) 8/25/76, (d) 8/26/76, (e) 8/27/76.

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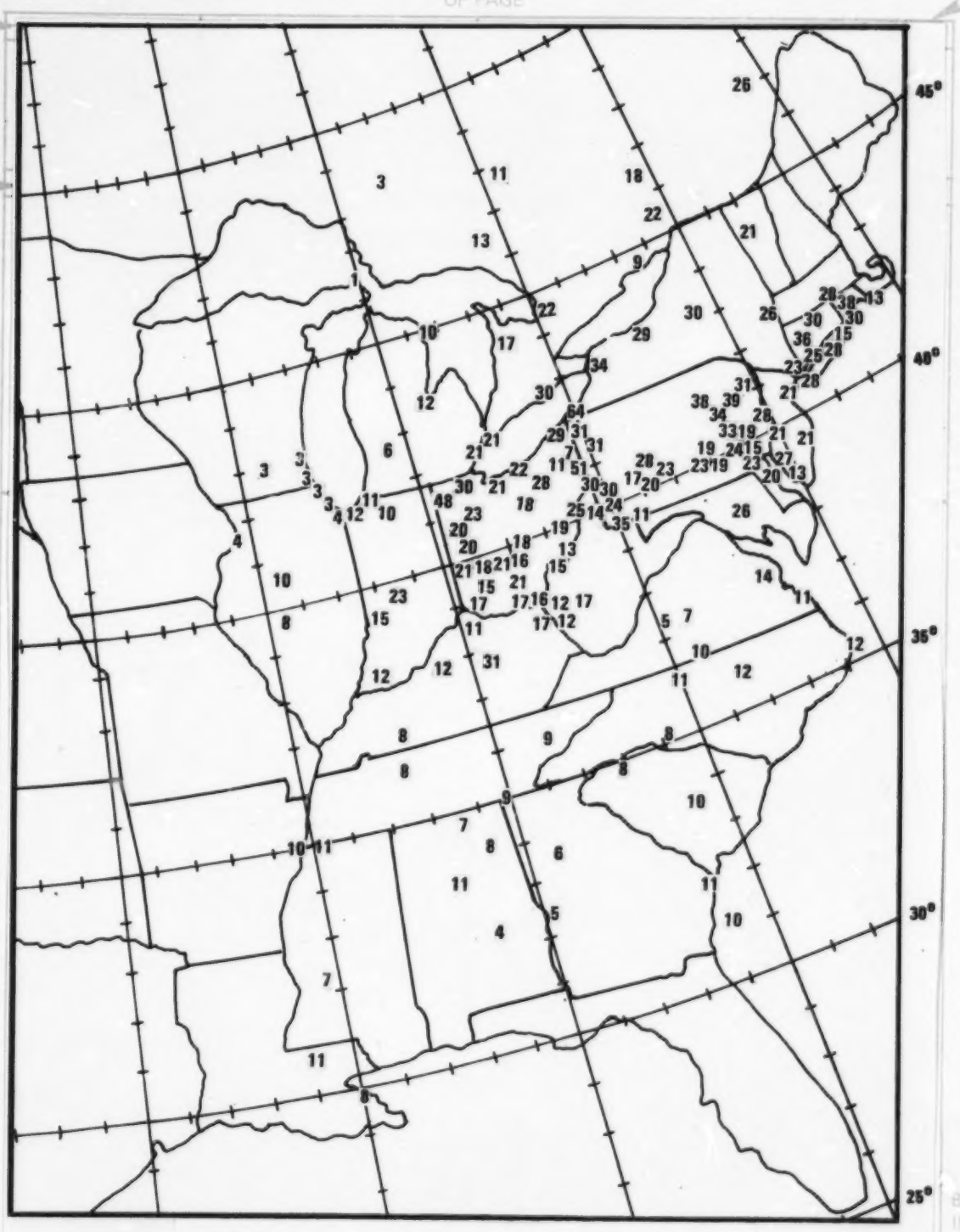

Figure 24. Sulfate concentrations ($\mu g/m^3$) August 28, 1976.

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the areas of stagnation, of high sulfate concentrations, and of restricted visibility were very similar; 5) on August 23, the frontal passage which ended the Korshover-designated stagnation period did reduce the sulfate concentrations and improve the visibility over southern Canada; 6) from August 23 to 27 there was good agreement between the areas of high sulfate concentrations and those of restricted visibility over southern Canada; and 7) on August 28, the area of high sulfate concentrations was about twice the size of the area of restricted visibility.

SYNOPTIC WEATHER AND ASSOCIATED SURFACE PHENOMENA

The daily synoptic weather patterns of August 17 to 28, 1976 are shown in Figure 2. Additional characterization of the weather is detailed by the weather summaries in Table 1 for each of six stations across the middle of the area affected by the stagnation and the restricted visibility. The following are shown: maximum daily temperatures, daily temperature departures from normal, percent of possible sunshine, and dates and amounts of rainfall.

The synoptic weather maps in Figure 2 show a surface high pressure area moved east from August 17 to 19 and then for 4 days moved southwestward. When this high was centered over Missouri on August 23, a front pushed southward over the eastern United States. A high, centered over southern Canada on August 24, moved in a south-southeast direction and was off the coast of Virginia by August 26. The eastern United States remained under the influence of the western side of this high until the two cold fronts (shown on the map of August 28) passed through the area on August 29.

The associated weather (Table 1) shows there were marked differences between the two high pressure areas. Although the sunshine was abundant during the August 16-22 period, the temperatures were generally in the 70's and 80's (°F) or near-normal to as much as 13° (F) below normal; the first high was associated with relatively cool weather and few clouds. The front which moved over the area on August 23 was not accompanied by rain and, except for Albany, had only a small effect on the temperatures. After August 23, maximum temperatures were mostly in

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TABLE 1. Maximum Temperatures (°F)/Temperature Departures from Normal (°F)/Percent Sunshine, and Rainfall, Six Stations, August 16 to 28, 1976.

Station	Date August 16	17	18	19	20
Chicago IL	73/-13/89	80/-10/100	84/-3/98	86/1/100	87/3/99
Indianapolis IN	79/-6/96	81/-5/100	82/-4/97	83/-2/96	84/0/95
Detroit MI	78/-7/100	85/-4/100	87/-1/99	88/-1/98	89/1/100
Columbus OH	76/-8/94	77/-9/100	81/-5/100	82/-1/86	81/-2/100
Harrisburg PA	76/-6/100	82/-4/100	81/-3/100	78/-6/100	82/-3/100
Albany NY	73/-4/58	82/-3/96	78/-5/100	78/-7/100	86/0/96

Station	Date August 21	22	23	24	25
Chicago	86/3/55	90/5/98	84/5/24	84/3/79	85/6/1
Indianapolis	85/1/86	86/2/63	88/5/51	86/6/50	80/3/19
Detroit	87/0/90	92/6/95	91/7/70	88/6/85	89/7/44
Columbus	83/-2/85	84/2/80	87/3/65	85/2/29	84/5/0
Harrisburg	86/0/100	89/5/100	86/3/100	84/4/86	84/5/75
Albany	89/6/88	90/8/59	82/2/59	79/-1/94	84/-1/84

Station	Date August 26	27	28	Rainfall Dates and Amounts (inches)
Chicago	88/7/71	96/13/70	86/4/78	8/26 0.02; 8/28 0.13
Indianapolis	85/4/26	88/7/82	86/3/60	8/25 0.08; 8/26 T.
Detroit	90/10/41	95/12/74	85/3/62	8/25 T; 8/26 T; 8/27 T; 8/28 0.03
Columbus	77/1/17	83/6/20	85/7/45	8/25 0.28; 8/26 0.45; 8/27 T; 8/28 1.49
Harrisburg	89/8/8	78/3/16	83/5/41	8/27 0.03
Albany	85/1/31	78/5/27	84/9/14	8/26 0.69; 8/28 0.38

T = Trace

Additional Observation - Excluding Chicago, most stations had fog and low clouds on August 26 to 28.

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the 80's (°F) with a few in the 90's and the average temperatures ranged from near normal to as much as 13° (F) above normal. From August 26 to 28 there was fog, low clouds and precipitation. The second high was relatively warm and, toward the end was moist (fog, low clouds, and precipitation).

Thus, the days before August 23 had cool temperatures and abundant sunshine (relatively clear skies), while from August 23 to 28 there were high temperatures and abundant sunshine at the beginning, but moist air on the last 3 days. When there was abundant sunshine both ozone and sulfate concentrations were high; but, when the air was warm and moist only the sulfate concentrations were high. This latter result supports the finding of Hidy et al.[16] that high sulfate concentrations occur in warm, moist air.

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TRAJECTORIES

The calculated transport in the layer from the surface to 1000 m for each day from August 16 to 28 is depicted in Figures 25 to 37. These trajectories for the dozen locations serve as indicators of transport between source-areas and receptor-areas. Major emphasis is given to the idea that the indicated transport may have contributed to the stagnation, the restricted visibility, and the moderate or high concentrations of each pollutant.

Pictorial aids in evaluating the likelihood of upwind areas being sources of precursors are included in three figures in the appendix (Figures A-1, A-2, A-3). Figure A-1 shows the point source emissions of nitrogen oxide (the precursor of ozone) by 80 km grid squares for the eastern United States, and Figure A-2 shows the area sources of the same pollutant. Typically, at sufficient distances (that is, distances which permit enough time for the photochemical reactions to produce ozone in the polluted air mass) downwind of large sources of nitrogen oxide emissions, there is a greater potential for ozone problems to develop than there is elsewhere. Figure A-3 shows the point sources of sulfur dioxide (the major precursor of sulfates). Point sources are responsible for more than 90 percent of the total sulfur dioxide emissions.

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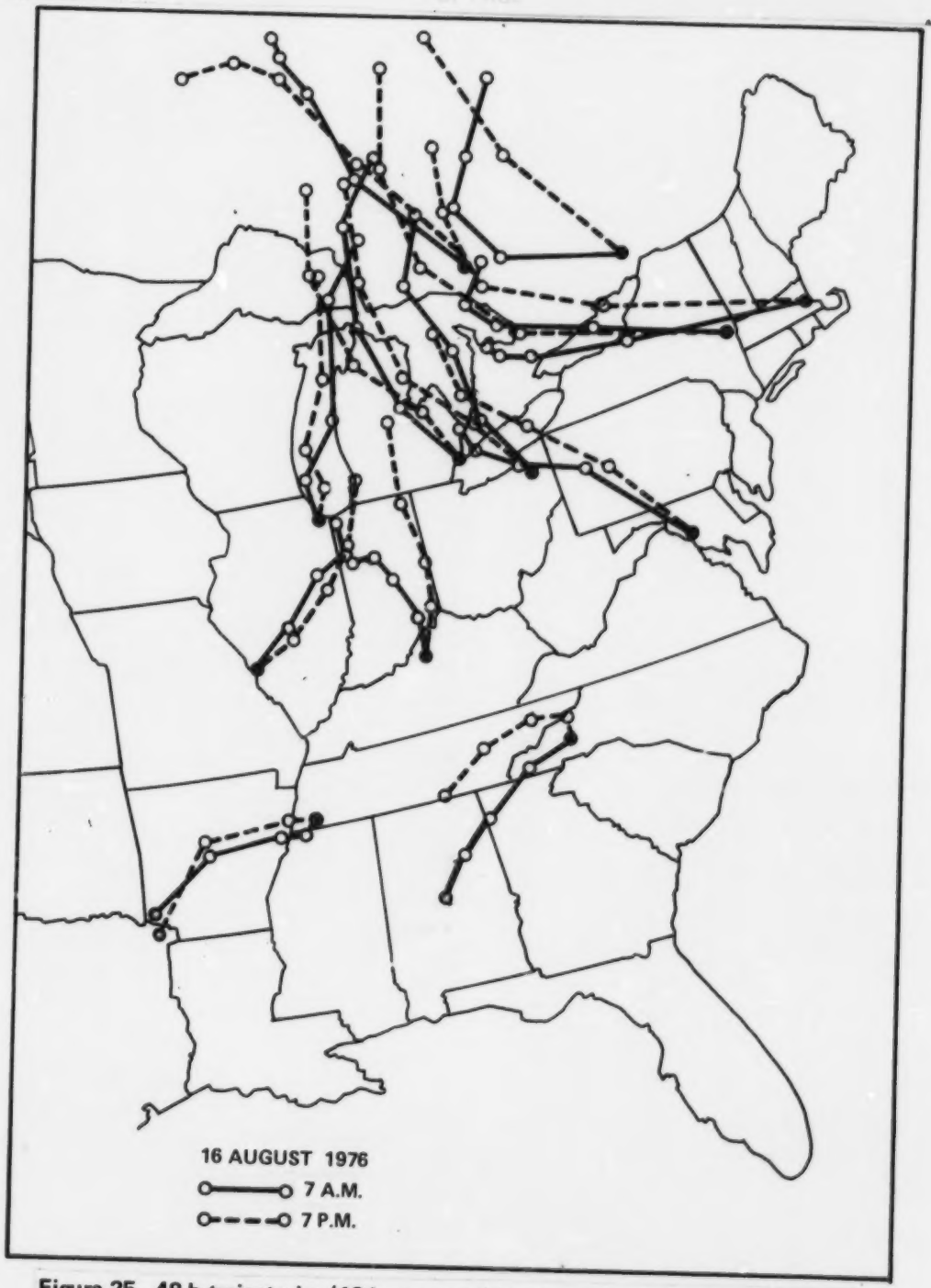

Figure 25. 48-h trajectories (12-h segments) for layers of air between the surface and 1000 m for selected cities, August 16, 1976.

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The transport for August 16 (Figure 25), as indicated by both the morning and evening trajectories, was from the west through north for the northern two-thirds of the depicted area. The trajectories show a flow from the north which explains the low temperatures. Ozone concentrations on this day (Figure 7) were generally low. The large area with moderate and high ozone concentrations centered around New Orleans was associated with transport from the south. This was determined from trajectories not shown in this report. These concentrations of ozone must have been due either to local sources (Figures A-1 and A-2) or to unknown sources in the Gulf of Mexico. The trajectories indicate that the source areas for the high sulfate concentrations (Figure 20) over the northeastern United States were to the northwest to north. The southeastern United States was to the south of a cold front for part of the day but north of the front by evening. The trajectories for that area show that the air influx was mostly from the southwest to west (with a short northerly component in the most recent 12 hours). The high sulfate concentrations over the eastern United States came from many directions. Possibly because the high sulfate concentrations were not uniformly spread through one large area, or because the concentrations were only slightly in excess of 10 $\mu g/m^3$, the sulfate concentrations were not reported to have had an effect on the visibility[5].

The transport on August 17 (Figure 26) was predominantly from the northwest through northeast, temperatures remained low in the stagnation area, and there were numerous widely separated areas in the west with moderate ozone concentrations (Figure 8). All of the polluted areas except the Chicago area had flows from the north and northeast; the most recent 12-hour flow at Chicago (a major source area according to Figures A-1 and A-2) was from the southeast and the moderate ozone concentrations were immediately downwind of that area. The sulfate data, limited to Canadian stations, showed no areas of high sulfate concentrations. (Figure 21).

On August 18 , the 48-hour trajectories show a clockwise flow around a center over Wisconsin (Figure 27). The influx into the stagnation area was primarily from the northeast, and the temperatures were

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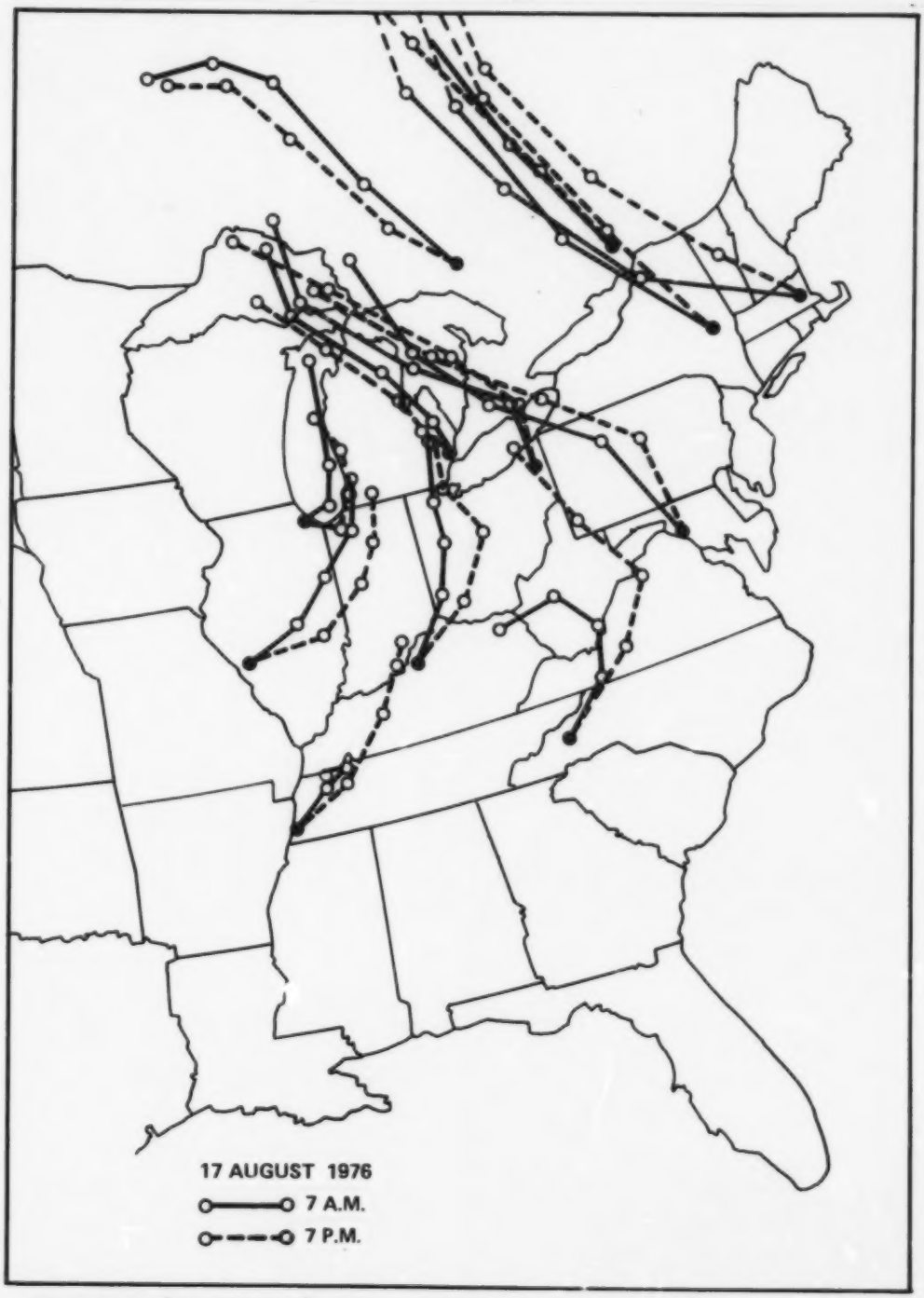

Figure 26. 48-h trajectories (12-h segments) for layers of air between the surface and 1000 m for selected cities, August 17, 1976.

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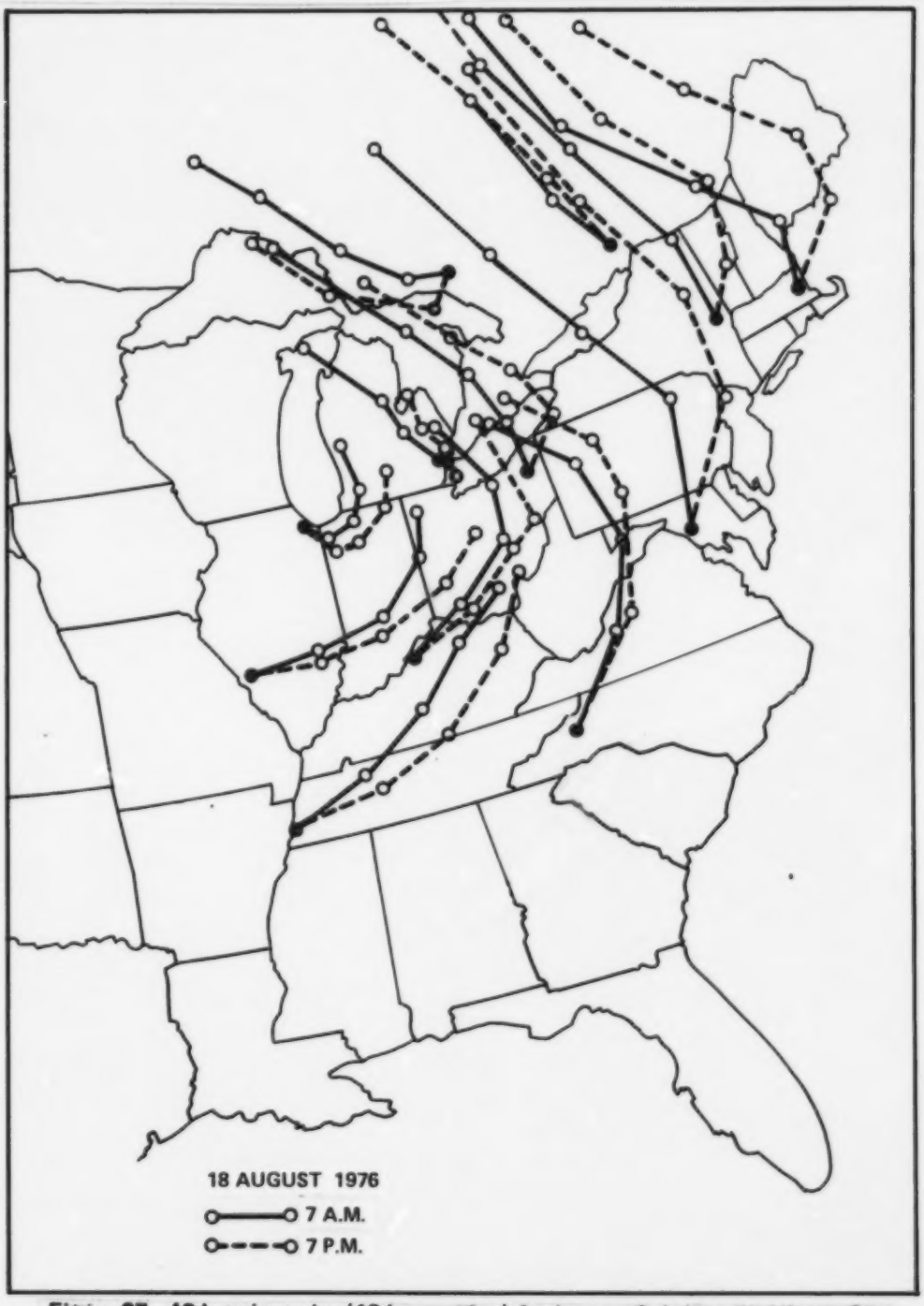

Figure 27. 48-h trajectories (12-h segments) for layers of air between the surface and 1000 m for selected cities, August 18, 1976.

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starting to moderate (Table 1). The source-receptor relationships (see Figures A-1, A-2 and 9) for the high ozone concentrations were from the area to the northeast into the Philadelphia area, from the area to the north into southeastern Michigan, and from the Chicago-northwestern Indiana area into the southeastern coastal area of Wisconsin. Almost all of the western half of the area shown in Figure 9 had moderate or high concentrations and the inflow was predominantly from the east. The high sulfate concentrations in western Ontario (Figure 21) were associated with a flow from a major source area to the west (Figure A-3).

The trajectories for August 19 (Figure 28) again show the dynamics involved in this transport. In the surface-to-1000 m layer there was a slow-moving high in the Lake Huron region with a marked clockwise movement of air about it. Near the center of the high the air movement was relatively slow and in places erratic while at greater distances the flow was more rapid and more organized. The flow into the area of moderate ozone concentrations (Figure 10) was from the north through east. The high sulfate concentrations in western Ontario on August 19 (Figure 21) were associated with a flow over major sources (Figure A-3) to the south and southwest.

The trajectories for August 20 (Figure 29) show that the high was over the eastern Great Lakes and New England. There were three elongated, large areas of high ozone concentrations (Figure 11) and each was associated with a large source area of precursors (Figures A-1 and A-2): 1) southeastern Wisconsin northward along the Wisconsin coast was associated with the source area around metropolitan Chicago; 2) a broad area including western and northeast Ohio and east central Michigan was associated with a flow from western Pennsylvania and 3) the area along the Atlantic Coast between Massachusetts and Delaware was associated with a flow from areas to the northeast. The area of moderate ozone concentrations was mostly to the southeast of the high pressure center and had flows from the east. Southern Ontario had high sulfate concentrations (Figure 21) and air coming from the southwest and west. In spite of the high sulfate concentrations over the broad area and a flow from a prime source area (Figure A-3), there was no indication of restricted visibility

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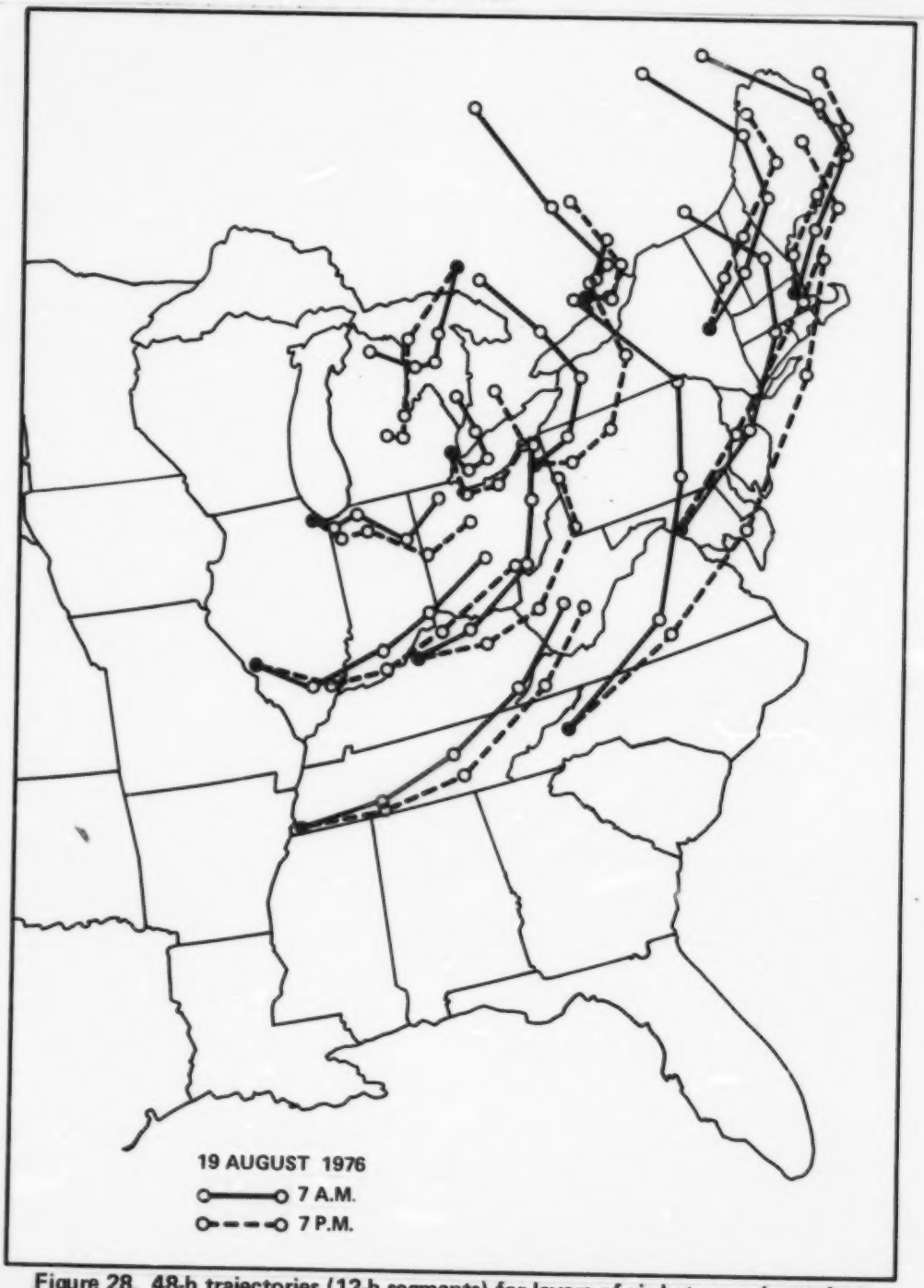

Figure 28. 48-h trajectories (12-h segments) for layers of air between the surface and 1000 m for selected cities, August 19, 1976.

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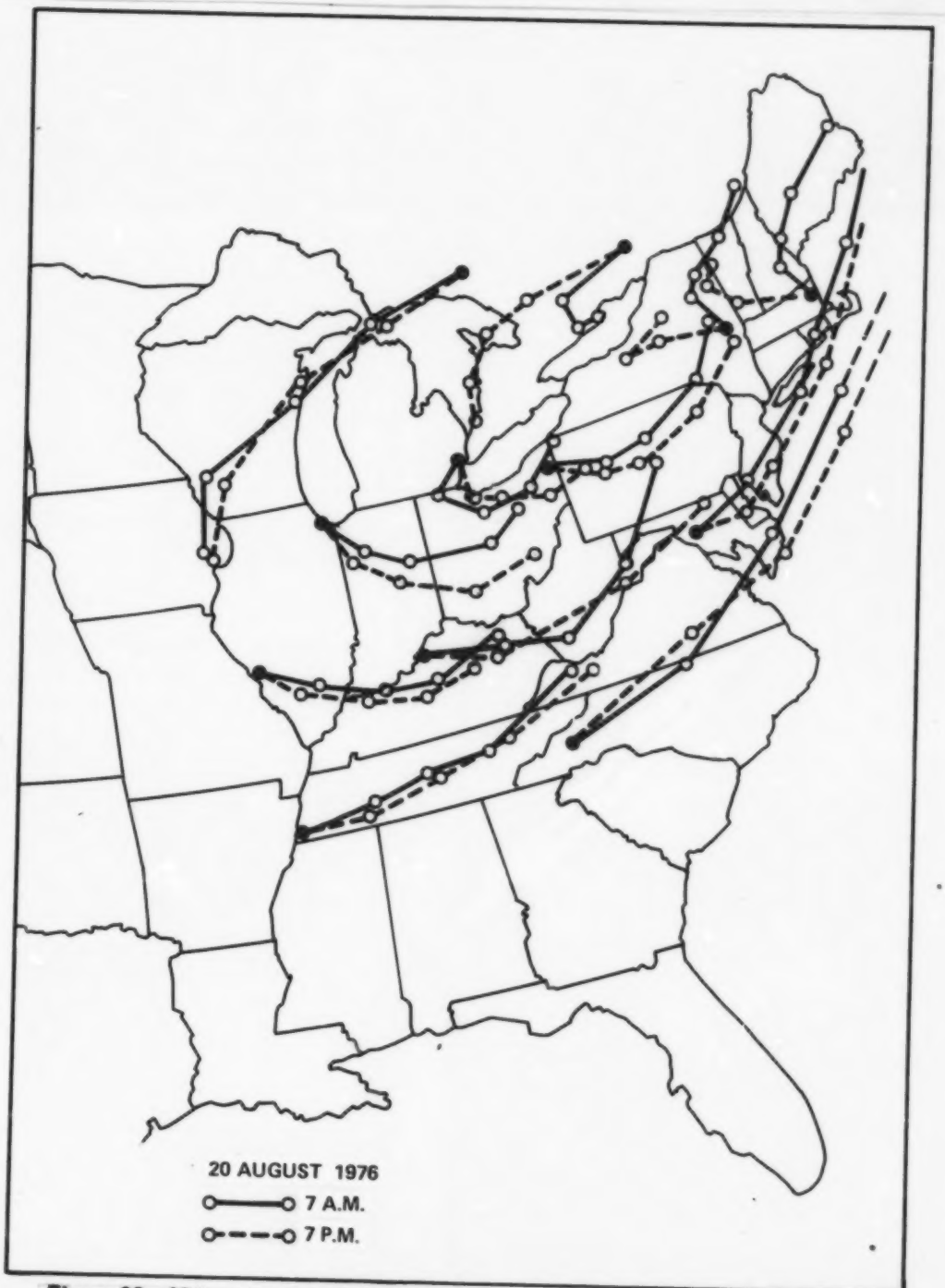

Figure 29. 48-h trajectories (12-h segments) for layers of air between the surface and 1000 m for selected cities, August 20, 1976.

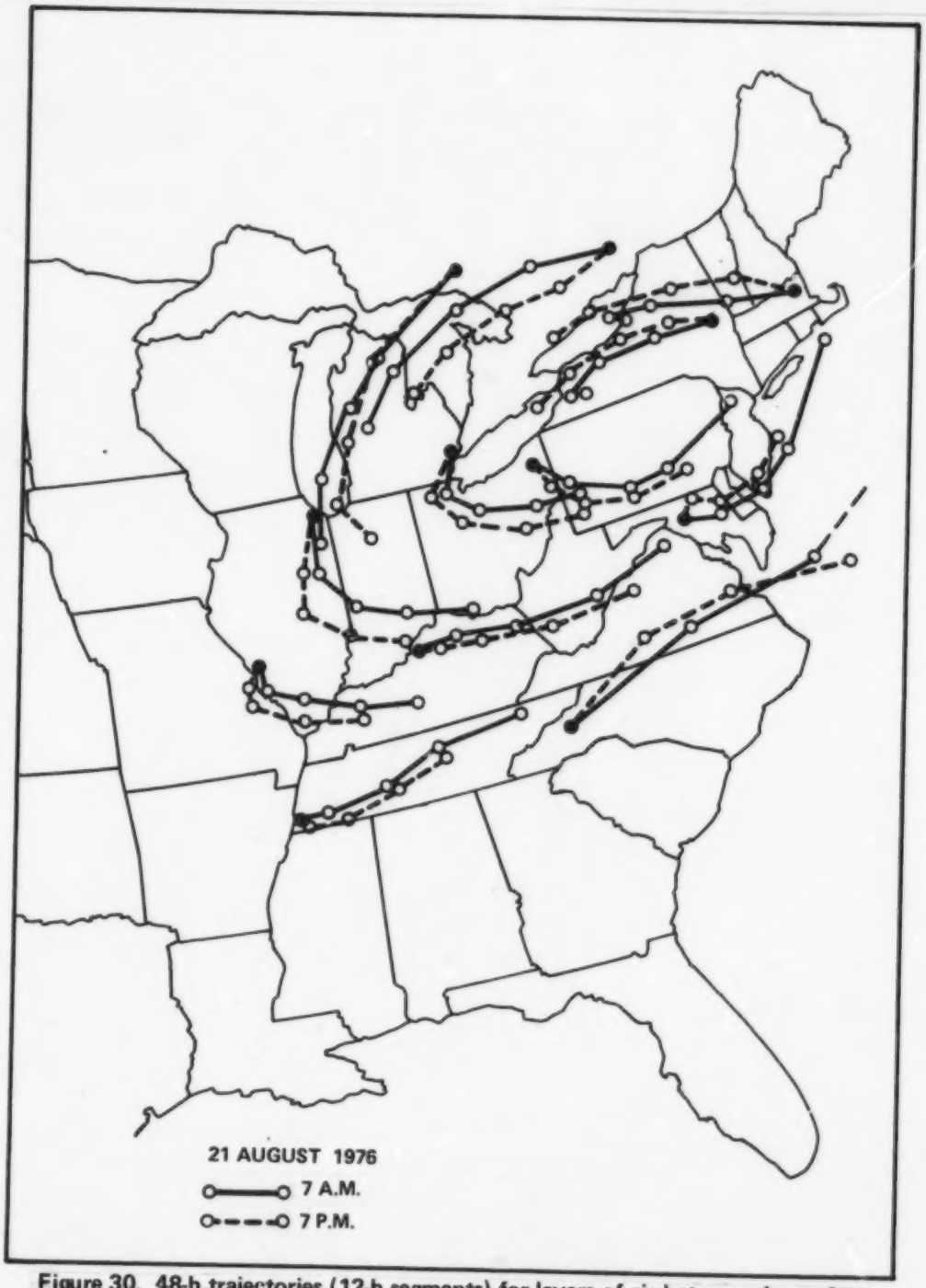

Figure 30. 48-h trajectories (12-h segments) for layers of air between the surface and 1000 m for selected cities, August 21, 1976.

(Figure 2).

On August 21 (Figure 30) the center of the clockwise flow was over Pennsylvania. The three large areas with high ozone concentrations of August 20 (Figure 12) reappeared with expanded boundaries. The source-receptor relationships were unchanged. There were several other areas with high ozone concentrations including a large one over eastern Louisiana. The concentrations over Louisiana were high from August 19 until August 28. The flow into the area (shown in trajectory analyses not included in this report) remained practically unchanged from August 19 through August 22 and was from the east-northeast, an area with relatively few sources in upwind areas outside of Louisiana (Figures A-1 and A-2). From August 23 to 28 each 48-hour inflow was from no farther away than southern Mississippi or from over the Gulf of Mexico. The general hypothesis with regard to Louisiana, which was not in the stagnation area nor a part of the large restricted visibility area, was that it had high concentrations that did not appear to be associated with sources of precursors at great distances from Louisiana. The St. Louis area, which also had high ozone concentrations on August 21 associated with an influx of air from the south, may have had pollution from local sources. Ozone concentrations of 8 pphm or more occurred over most of the eastern United States. The high sulfate concentrations of August 21 over southern Ontario (Figure 21) were still associated with flows over major source areas to the southwest and west (Figure A-3).

By August 22 (Figure 31) the marked clockwise flow was starting to break down. There were still areas of high ozone concentrations (Figure 13) in southeastern Wisconsin, along western Ohio and eastern Michigan, and along the Boston-to-Washington corridor. However, the source areas appeared to change from previous days for each of those polluted areas. The inflow into the areas of high ozone concentrations generally had a westerly component. Regardless of the source of air over the eastern United States, it had a moderate or high ozone concentration; the entire air mass had excessive ozone concentrations. Most of the August 22 sulfate data (Figure 22) came from Ohio and Pennsylvania. The trajectories for this day into the areas with high concentrations were among the shortest

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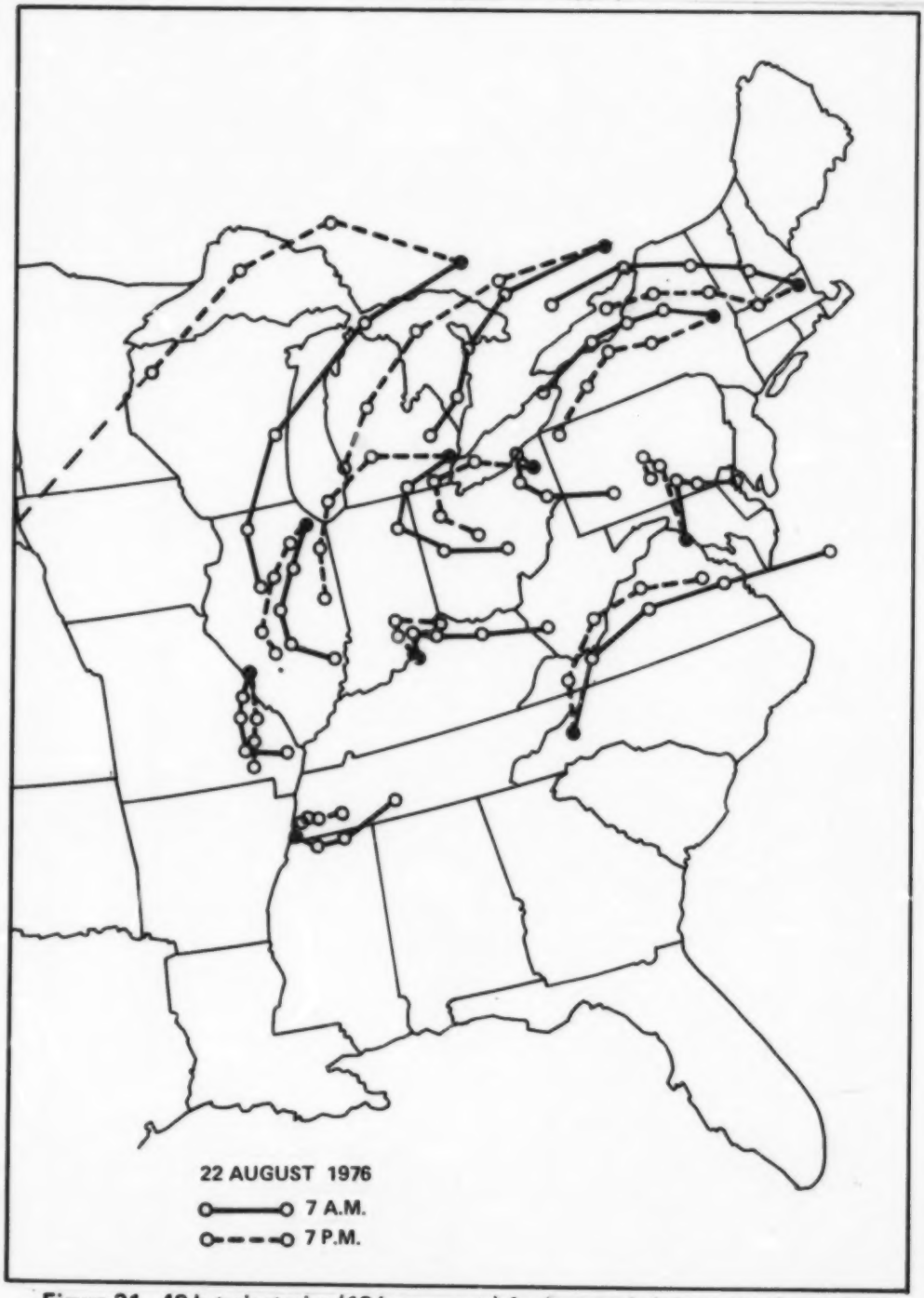

Figure 31. 48-h trajectories (12-h segments) for layers of air between the surface and 1000 m for selected cities, August 22, 1976.

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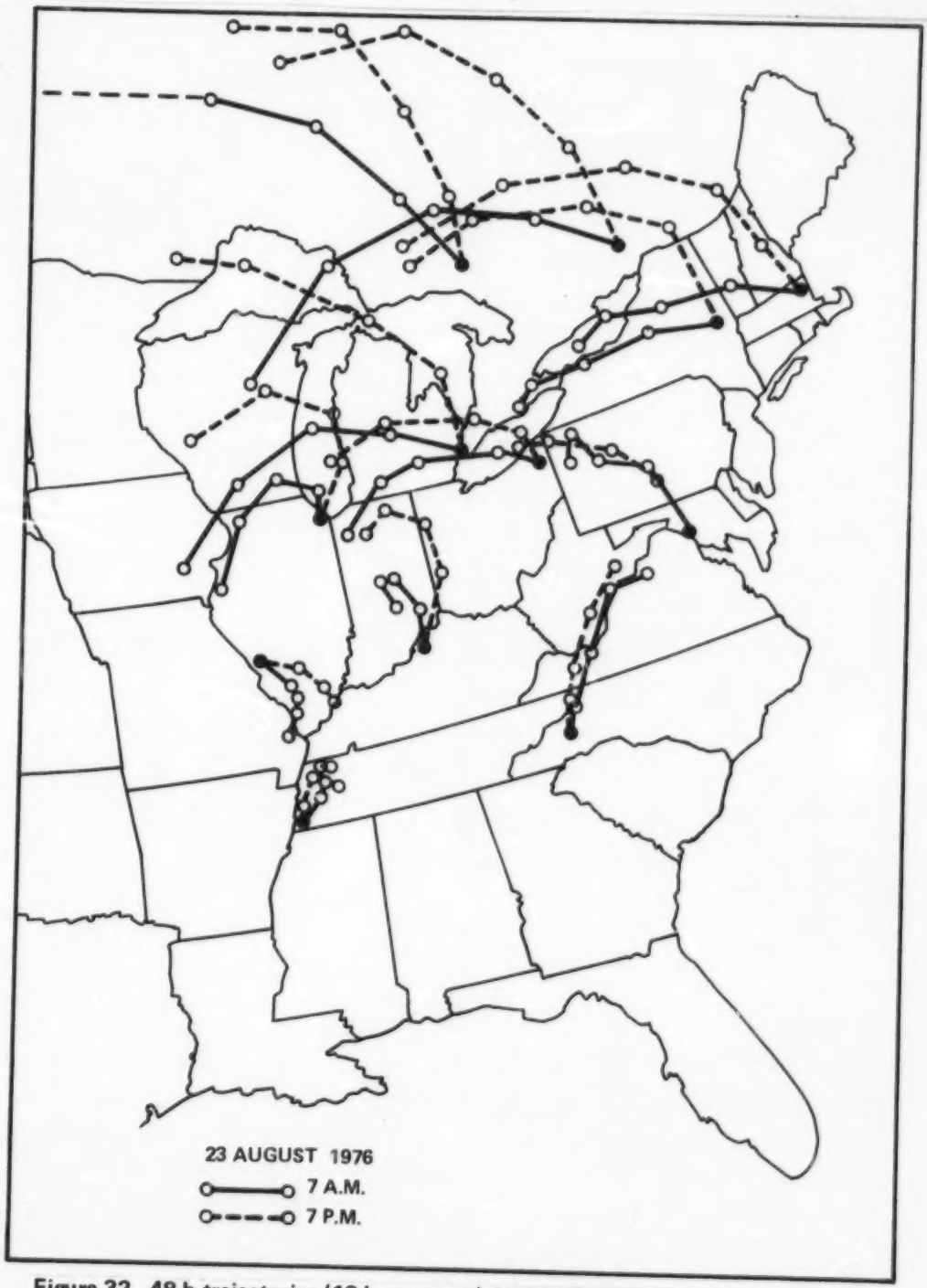

Figure 32. 48-h trajectories (12-h segments) for layers of air between the surface and 1000 m for selected cities, August 23, 1976.

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that occurred during the thirteen-day stagnation. However, the flow brought both high sulfate concentrations and unrestricted visibility to Pennsylvania.

On August 23 (Figure 32), the flow was mostly from the north, particularly during the last 12-hour period. However, unlike the trajectories following the front of August 16, these post-frontal trajectories show a more westerly component and were associated with higher temperatures (Table 1). This post-frontal flow did reduce the size of the area with moderate ozone concentrations (Figure 14) and eliminated the area with high ozone concentrations near Chicago. The flow across the source area around Chicago (Figures A-1 and A-2) was toward the south, an area with no recording sites (Figure 14). In addition, the flow moved and reduced the area of high ozone concentrations in western Ohio, and lowered the concentrations a modest amount along the northeast coast. The sulfate concentrations over western Ontario (Figure 23) were lower than they were on the day before. Thus, the northerly flow accompanying the front of August 23 did reduce the ozone and sulfate concentrations in some places and improve the visibility.

Whereas the trajectories from the north had a marked westerly component on August 23, they had a marked easterly component over the eastern United States on August 24 (Figure 33). Ozone concentrations (Figure 15) moderated in response to the continued strong winds shown by the long trajectory segments from the north. Again, as with the initial days after the first frontal passage, most of the areas with moderate and high ozone concentrations were in the western half of the eastern United States. Most of the flow into these areas recorded in the most recent 24 hours was from the east. The parts of Kentucky and Tennessee with high ozone concentrations were downwind of source areas in eastern Ohio, western Pennsylvania, and West Virginia (Figures A-1 and A-2). Another large area of high concentrations was over Louisiana and Mississippi (discussed under August 21). The sulfate concentrations over southern Canada (Figure 23) were low in response to flows of clear air out of the north (Figure A-3). The area of restricted visibility was to the south of the international border (Figure 2).

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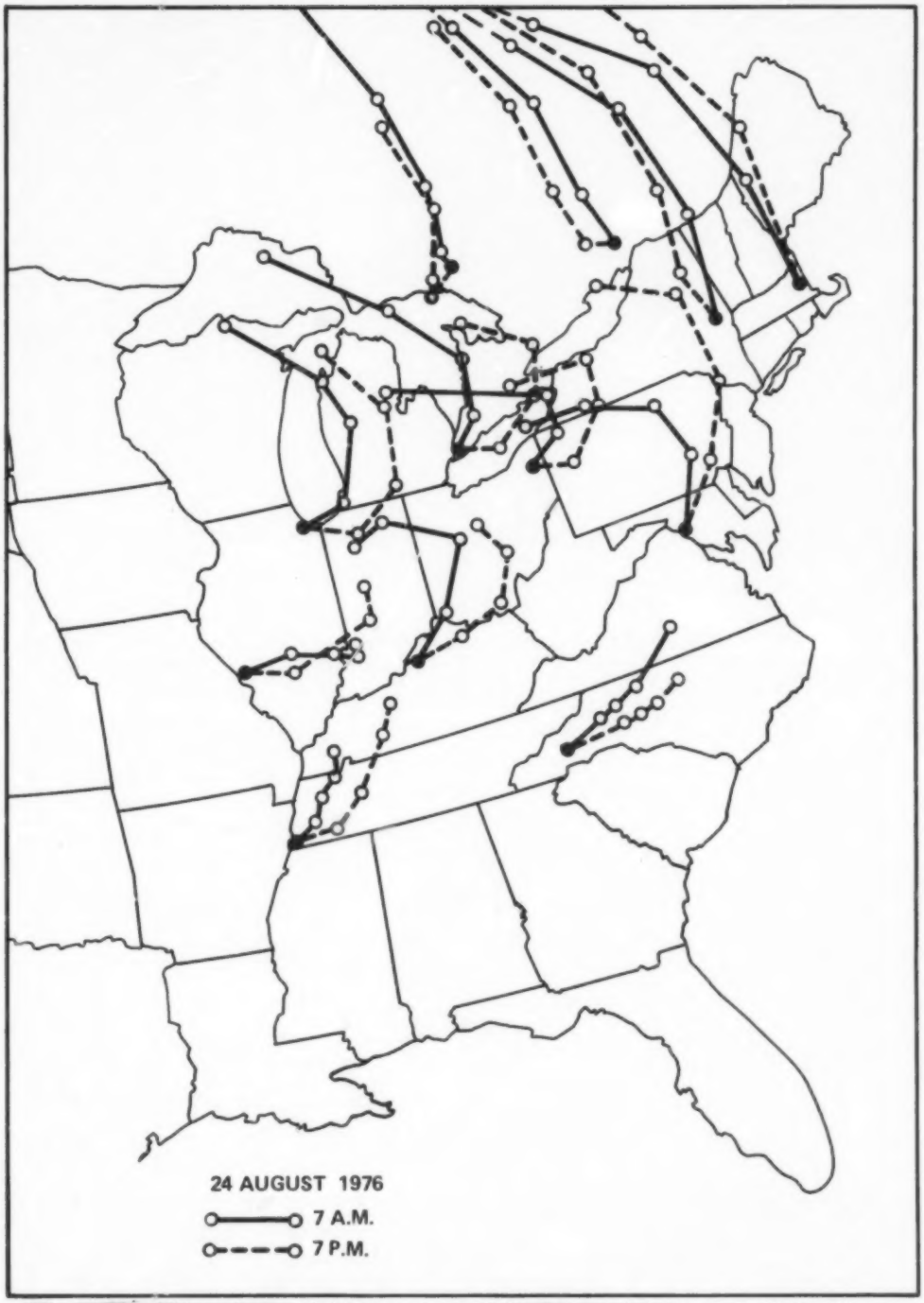

Figure 33. 48-h trajectories (12-h segments) for layers of air between the surface and 1000 m for selected cities, August 24, 1976.

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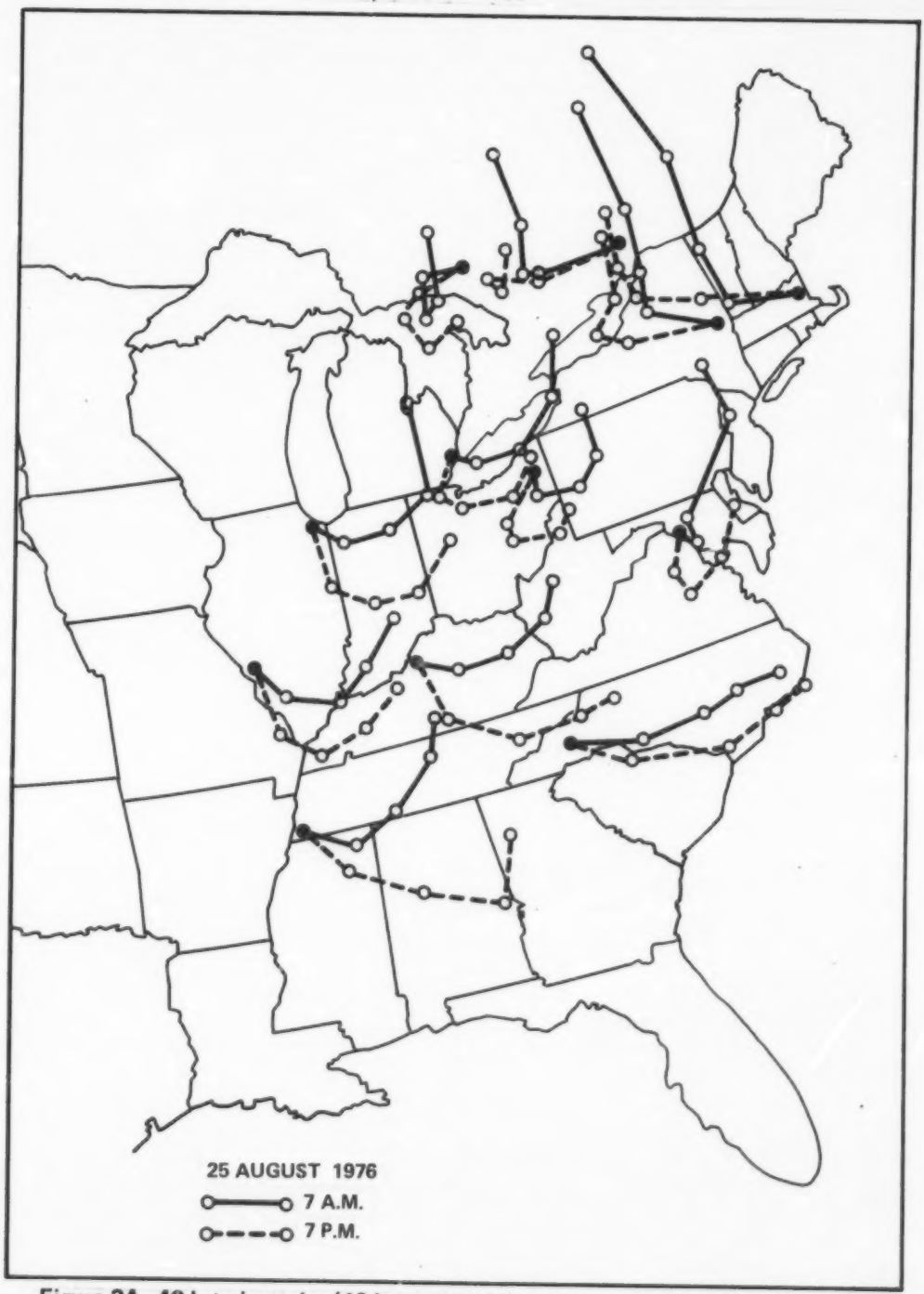

Figure 34. 48-h trajectories (12-h segments) for layers of air between the surface and 1000 m for selected cities, August 25, 1976.

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Flow on August 25 (Figure 34) over most of the eastern United States was from the east. The four elongated, distinct areas (Figure 16) of moderate and high ozone concentrations (southwest Illinois to upper Michigan, northern Kentucky to northern Michigan, southeast Ohio to northwest New York, northern Virginia to southeast Massachusetts) indicate that the south-to-north trajectories of the most recent 12 hours at most locations could have been prime contributors to the resulting concentrations. In each case the trajectories in the earlier 36 hours were over areas of relatively low precursor emissions whereas those for the last 12 hours were over source areas with larger emissions (Figures A-1 and A-2). Two of the areas between the areas of moderate and of high ozone concentrations had rainfall (see Indianapolis, Detroit and Columbus in Table 1) while the polluted areas themselves did not have precipitation. Extreme southern Canada had high sulfate concentrations (Figure 23) and restricted visibility in response to the flow over large source areas to the south (Figure A-3).

On August 26 (Figure 35) most of the air coming into the eastern United States was from the south and the temperatures were higher than normal (Table 1). Precipitation was becoming more widespread across the eastern United States on this date. The number of sites with moderate and high ozone concentrations was considerably smaller than it had been on the previous day (Figure 17). The rain and accompanying clouds greatly reduced the potential for photochemical reactions and the production of ozone from precursors. As noted earlier, sulfate concentrations were high in the warm, moist air. On August 26 (Figure 23) southern Canada experienced rainfall along with high sulfate concentrations because, as the trajectories indicate, the sample air passed over major source areas to the southwest.

On August 27 (Figure 36) the flow over most of the eastern United States and southern Canada was from the south-southwest through west. Along the northeast coast the concentrations of ozone were markedly reduced while elsewhere there was little change in the ozone concentrations (Figure 17). The sulfate values (Figure 23) remained unchanged except for some lowering of concentrations in extreme western Ontario.

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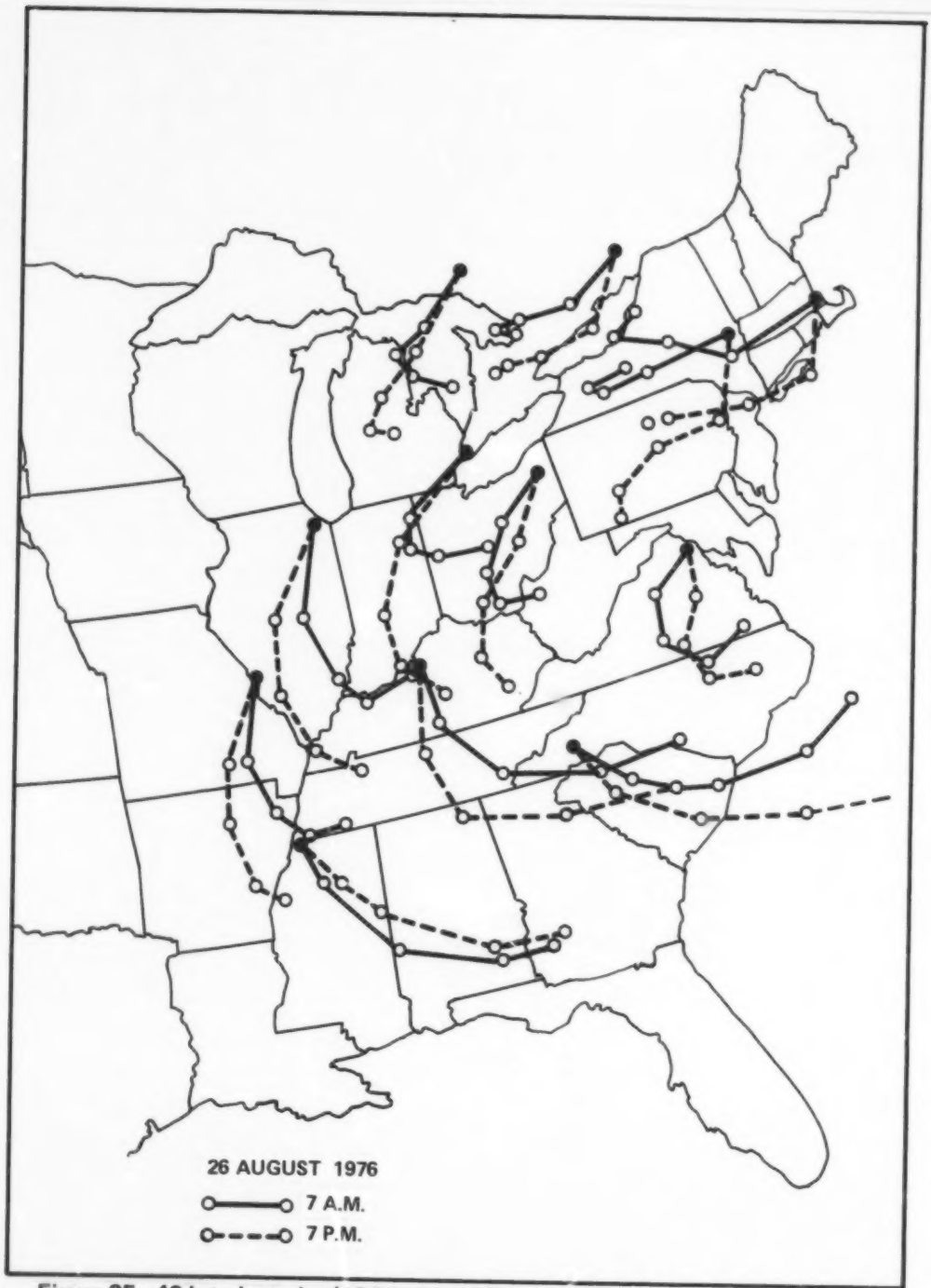

Figure 35. 48-h trajectories (12-h segments) for layers of air between the surface and 1000 m for selected cities, August 26, 1976.

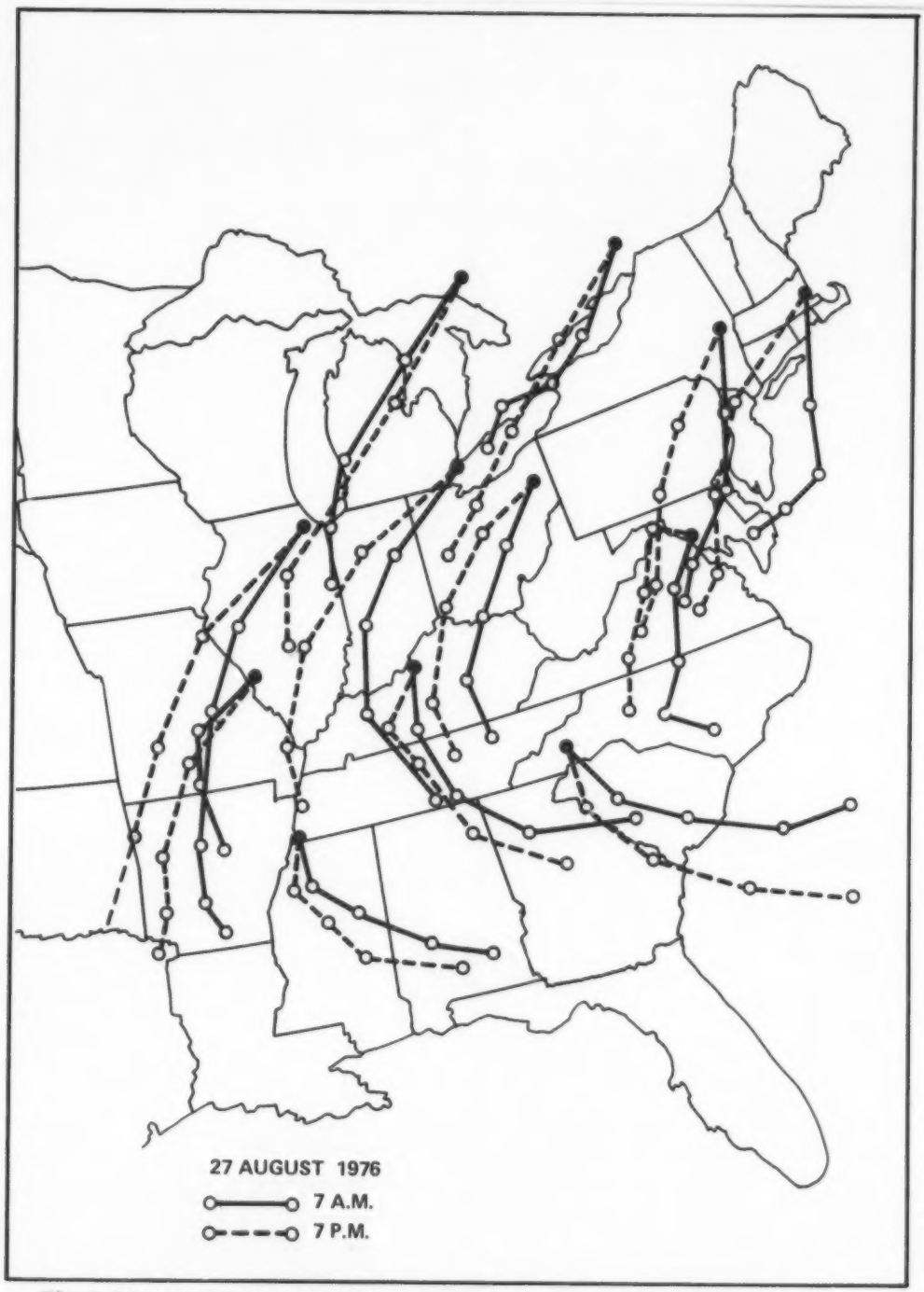

Figure 36. 48-h trajectories (12-h segments) for layers of air between the surface and 1000 m for selected cities, August 27, 1976.

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This was another day with widespread rain and, again, the rain and accompanying clouds may have kept the ozone concentrations low while having little effect on the sulfate. The area of restricted visibility covered much of the area with low ozone concentrations but where the sulfate concentrations were high, there was restricted visibility.

The flows over the eastern United States on August 28 (Figure 37) were predominantly from the southwest through west. Possibly in response to this flow and to more sunshine (the area of precipitation was less widespread) on this day there were more sites with moderate and high ozone concentrations of sulfates (Figure 19) than on August 27. The abundant sulfate data for August 28 (Figure 24) indicate that these flows were accompanied by high concentrations from Indiana and western Ontario in the west to New England and Maryland in the east.

Overall, the trajectory analyses indicate that: 1) there was a more northerly flow from August 16 to 22 than from August 23 to 28, partially accounting for the cooler air mass in the first period; 2) in spite of the almost continually shifting curvilinear flows, three north-south elongated areas of high ozone concentrations reappeared on many days; 3) hese three elongated areas showed high concentrations of pollutants even though there was a marked change in the indicated source areas from one day to the next; 4) on August 23, the strong flow from the north, coming behind the front, did temporarily and partially lower the ozone and sulfate concentrations and improve the visibility; 5) the concentrations of ozone gradually increased in the clockwise flow after August 23 while the skies were clear, but decreased when the cloudy, moist air arrived; 6) the high ozone concentrations over Louisiana almost every day were not directly associated with the stagnation area nor with the large area of restricted visibility, and did not appear to be associated with flows from sources outside of Louisiana; 7) the sulfate concentrations increased to high levels over Canada during the initial days of the stagnation when the flows were from within Canada (although eventually much of the influx was from south of the border); and 8) in spite of flows over major source areas of precursors of both pollutants[15] only sulfate concentrations remained high in the moist air.

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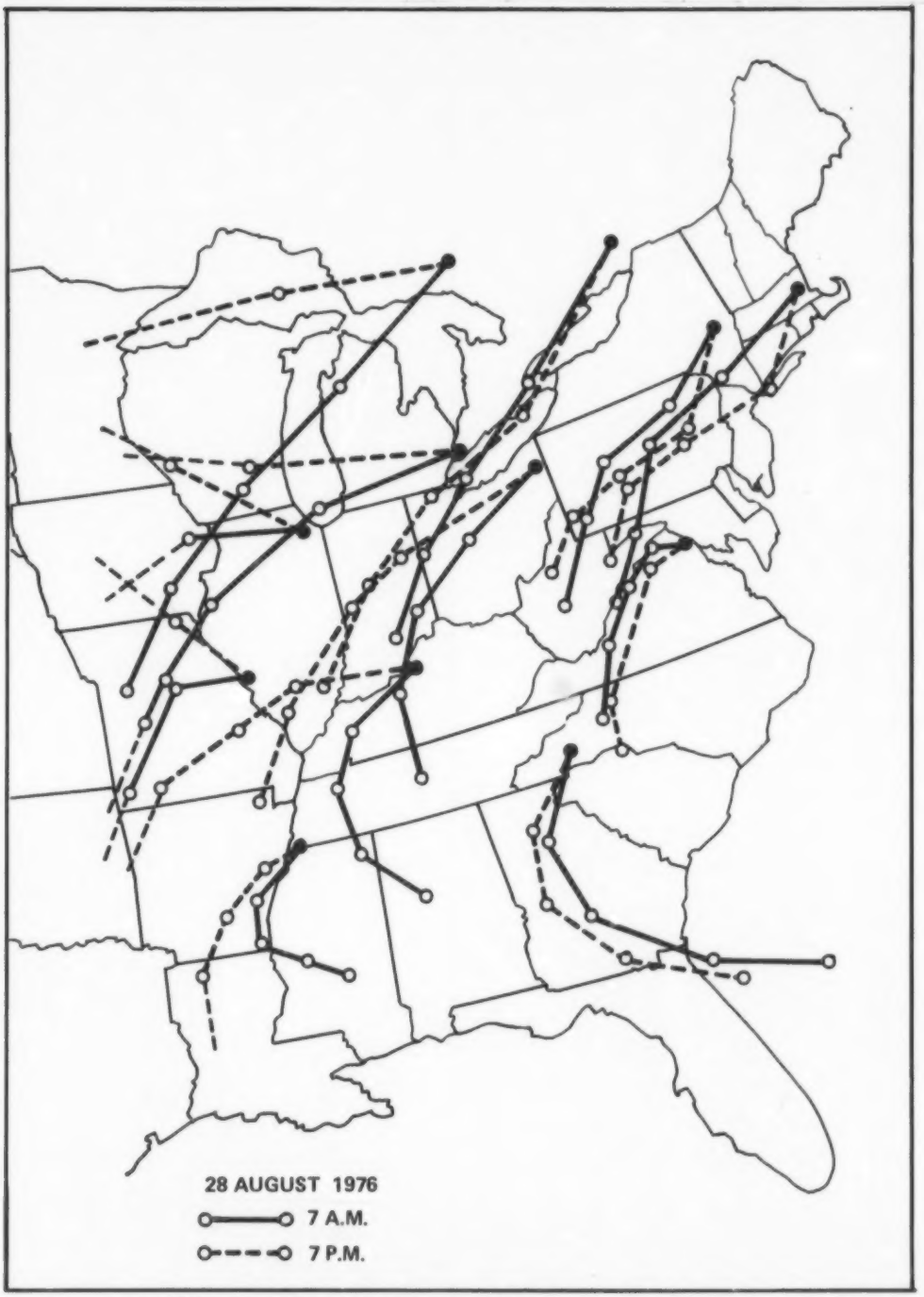

Figure 37. 48-h trajectories (12-h segments) for layers of air between the surface and 1000 m for selected cities, August 28, 1976.

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SECTION 5

SUMMARY

The analyses of the air quality and meteorological data for August 16 to 28, 1976 for the eastern United States and southeastern Canada, supplemented by the previous analysis of visibility data[5] provided the following results:

The atmospheric stagnation did not result in an accumulation of pollution sufficient to cause restrictions to visibility (that is, less than 7 miles visibility) over a large area until the sixth day of the episode. From the sixth to thirteenth day of stagnation there always was continuous restricted visibility over a large area.

The concentrations of total suspended particulates, carbon monoxide, and sulfur dioxide were never high and did not show increases during the stagnation. The concentrations of these pollutants were unaffected by the stagnation and did not appear to contribute to the visibility reductions.

The ozone concentrations increased to moderate and high levels during the first few stagnation days, then remained constant until the passage of the front on August 23. Concentrations were moderate or high over most locations until the warm, moist air moved over much of the area on August 25 and 26. There was poor spatial correspondence between the areas of moderate and high ozone concentrations and the areas of restricted visibility.

The sulfate concentrations were high over a large part of the eastern United States on the first day of stagnating conditions. Over Canada, the concentrations increased during the initial stagnation days and were then high until the frontal passage of August 23. On August 22 the sulfate concentrations were very high over large parts of the northeastern United States and southeastern Canada. The frontal passage of

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August 23 temporarily reduced the concentrations. By August 25, sulfate concentrations were again high over southeastern Canada; and, on August 28, very high sulfate concentrations were observed over a large area of eastern North America. Thus, the sulfate concentrations were high in the warm, moist air of the last 3 days of the stagnation period. Most of the time there was good spatial agreement between areas with high sulfate concentration and areas of restricted visibility.

The boundaries of the areas of restricted visibility appeared to change more in accord with changes in areas of high sulfate concentrations than with changes in the boundaries of areas of moderate and high ozone concentrations.

The trajectory analyses, while showing the well-organized anticyclonic flow that existed during the stagnation, also demonstrated that source-receptor relationships were constantly changing. The same three north-south elongated areas with high ozone concentrations reappeared many times, indicated either that there were sources of precursors in practically every upwind direction or that there were large area sources nearby which were not affected by directional shifts.

During the stagnation condition some pollutants attained high concentrations in time while others did not. There may have been a seasonal effect; if the stagnation had occurred in the cold season the results with total suspended particulate, sulfur dioxode, and carbon monoxide may have been different. Thus, concentrations of a pollutant can be low early in a stagnation period even though the concentrations may be high later. There seems little doubt that both Korshover and Lyons et al. properly identified a period when an air pollution episode developed. According to the Korshover semi-objective method, the episode ended with the passage of a weak front. The front, while separating two air masses, had so little contrast across it and was moving so slowly that its existence and location were hard to detect. This type of front is the exception to the rule that a front brings a clean, new air mass, and shows that the restrictive criterion for ending an episode with any frontal passage is a shortcoming of the Korshover technique.

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APPENDIX A

PERTINENT SOURCE EMISSION DATA

A recent publication by T. Clark[15] contains figures showing emissions of pollutants per 80 km grid square across the eastern United States and southern Canada. Three of these figures are reproduced here because they indicate likely source-areas for the release of ozone and sulfate precursors. Figure A-1, annual point source emissions of nitrogen oxides, and Figure A-2, annual area source emissions of nitrogen oxides, indicate the source areas (grids with higher numbers) of emissions which have a greater potential for being associated with high ozone concentrations in distant downwind areas (distant to the extent that sufficient time had elapsed for photochemical reactions to have produced ozone in the transported polluted air). Figure A-3, annual point source emissions of sulfur dioxide (point source emissions account for more than 90 percent of the total sulfur oxide emissions) indicate those areas which have the greater potential to be associated with high sulfate concentrations in distant downwind areas (again, distance is needed for the conversion of precursors to sulfates).

The source emission data summarized are based on a compilation that was completed in 1977.

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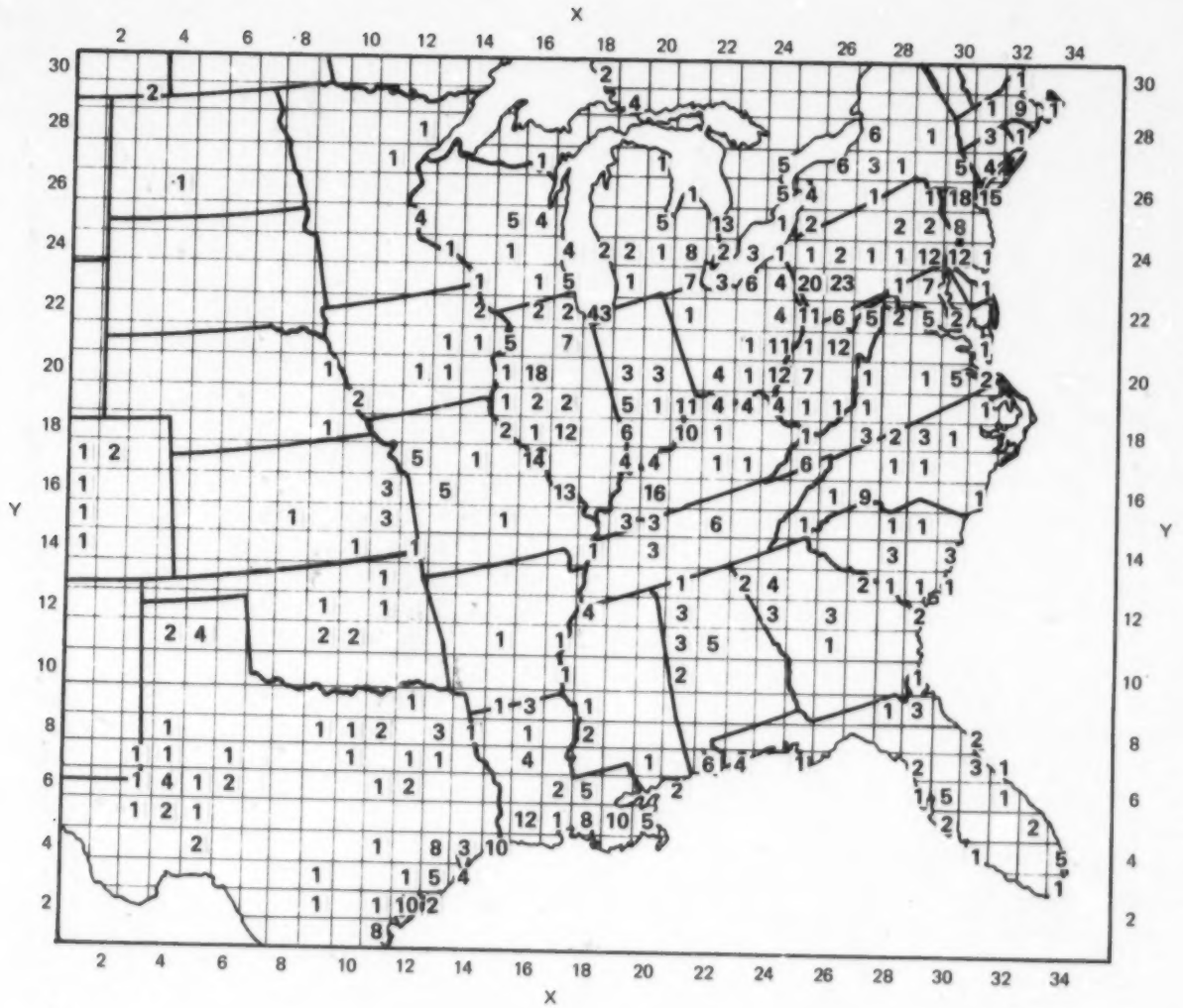

Figure A-1. Gridded annual point source emissions (10,000 tons/yr) of nitrogen oxides for the eastern United States and Canada (80 Km grid squares).

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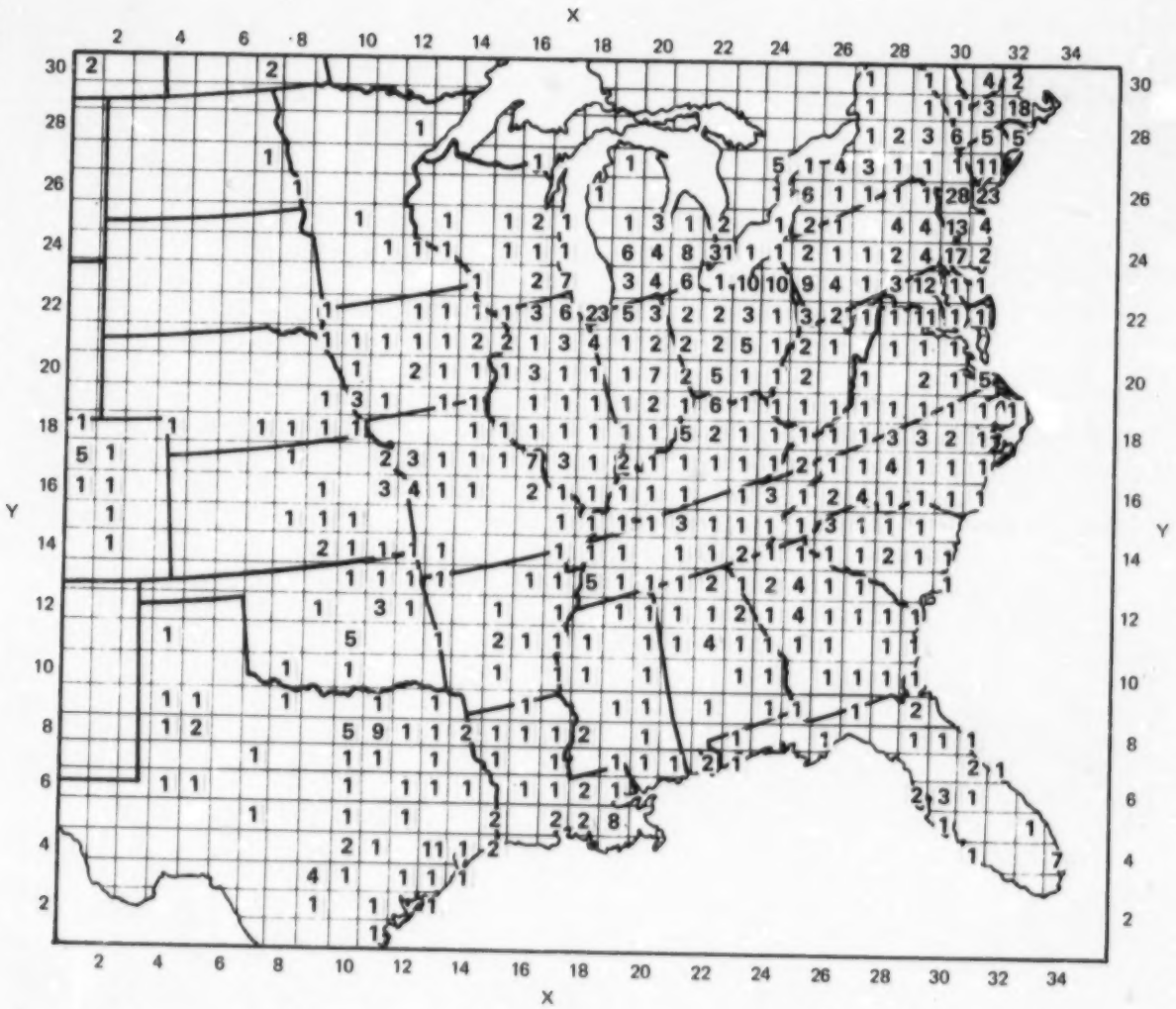

Figure A2. Gridded annual area source emissions (10,000 tons/yr) of nitrogen oxides for the eastern United States and Canada (80 Km grid squares).

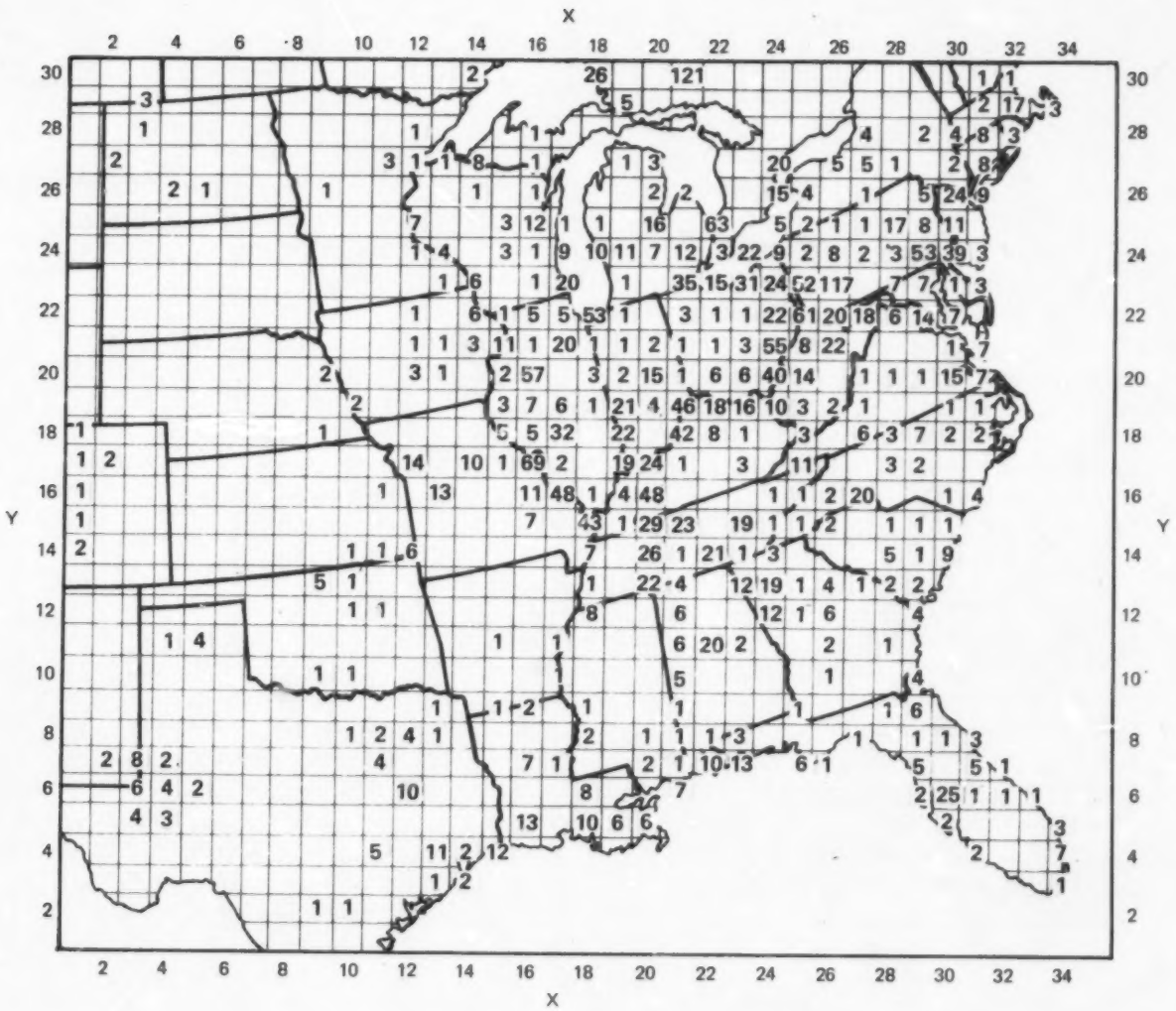

Figure A8. Gridded annual point source emissions (10,000 tons/yr) of sulfur dioxide for the eastern United States and Canada (80 Km grid squares).